HiLumi
HL-LHC PROJECT

Recent progress on noise estimation for HL-LHC circuits powering

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on behalf of WP6B

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CERN

Introduction

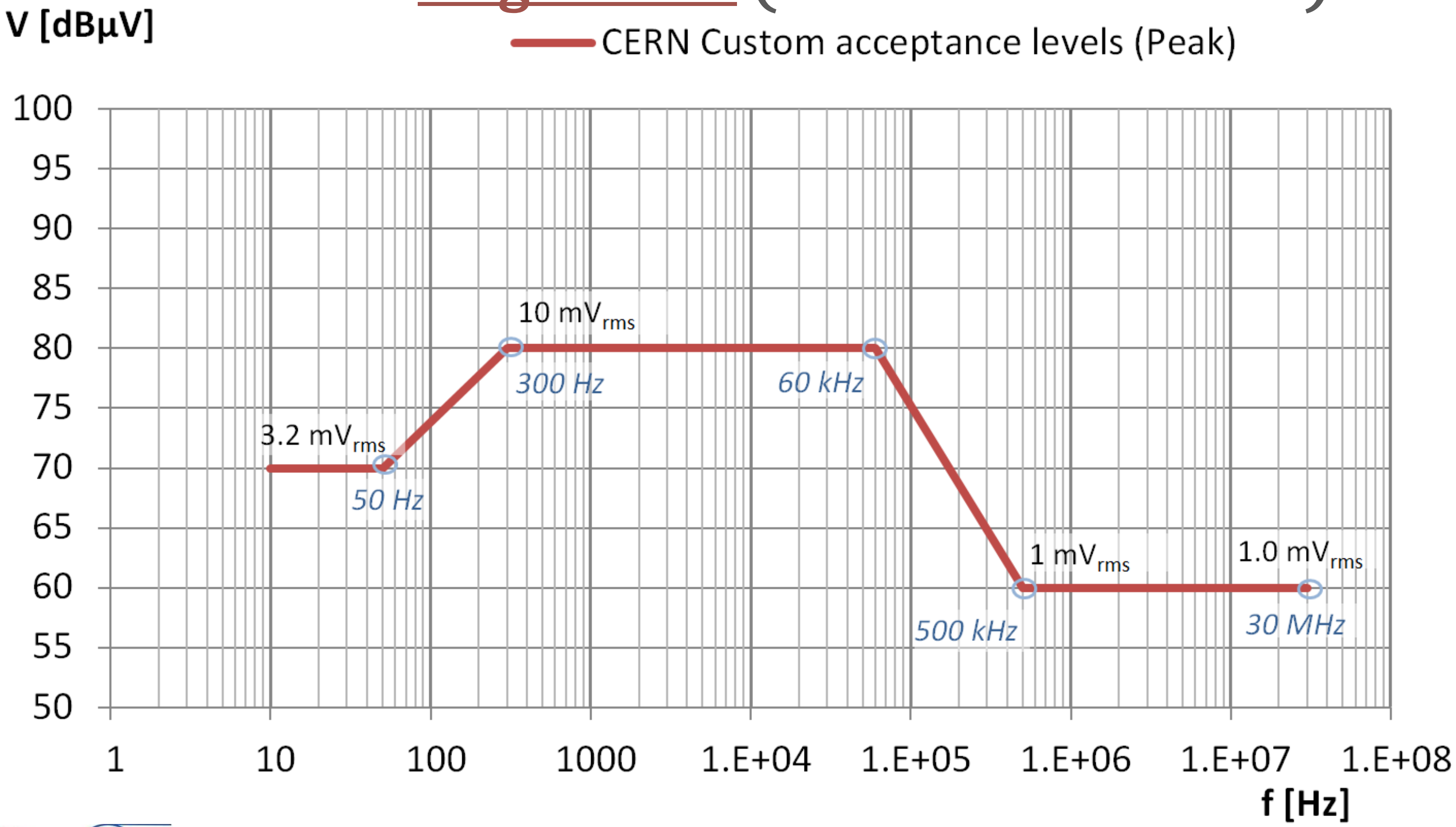
- Update of beam dynamics requirements for HL–LHC electrical circuits CERN-ACC-2019-0030[1] (being released)
  - Highlights:
    - the already "well-known" 0.1 ppm rms up to 0.1 Hz (or better)
    - as shown by Lucio WP6B is steadily progressing towards it
    - noise above 0.1 Hz and up to tens of kHz is still to be fully specified
    - a detailed decade-by-decade analysis is needed
    - Transfer Function from PC voltage to B-field is an important step

Transfer Function from PC Voltage to B-field

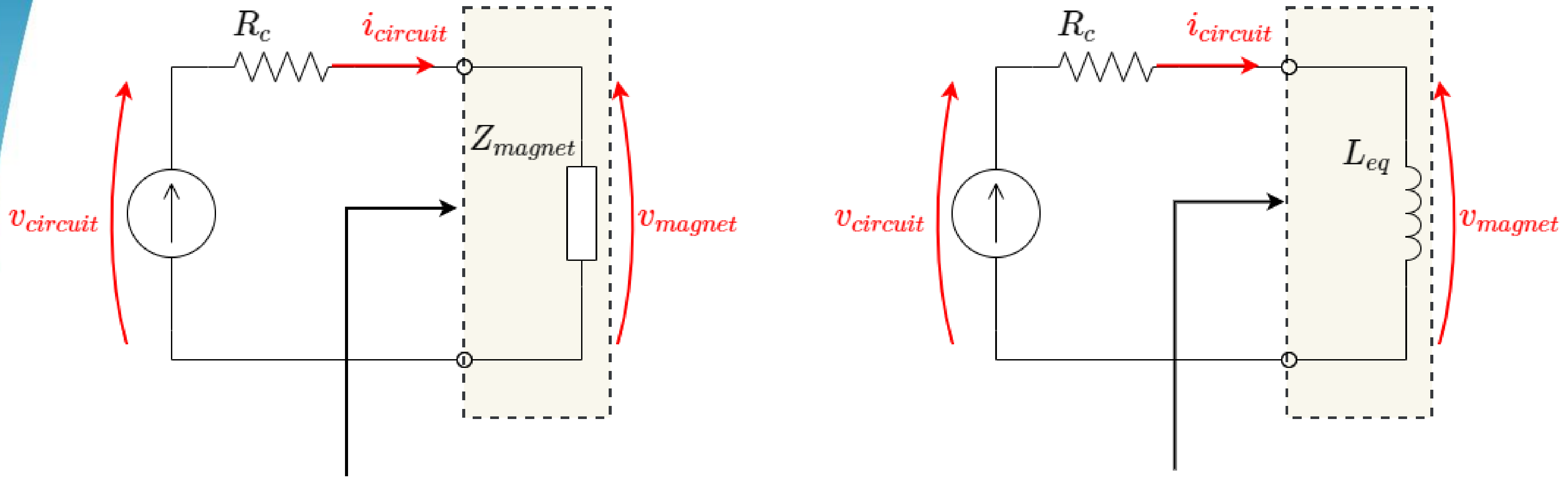
- **Current Control[1]:**
  - $B(f) \propto I(f)$ $\qquad f \leq$ few Hz
  - 0.1 ppm current noise $\rightarrow$ 0.1 ppm noise on the field "seen by the beam"
- **Voltage Control[1]:**
  - $B(f) = T_{\mathrm{B_m toB_b}}(f) \times T_{\mathrm{ItoB_m}}(f) \times T_{\mathrm{VtoI,circuit}}(f) \times V(f)$ $\qquad f >$ few Hz
  - many factors intervene to "lessen" the impact of voltage noise $V(f)$
    - $T_{\mathrm{B_m toB_b}}$: lowpass effect of the beam screen, cold bore etc…
    - $T_{\mathrm{ItoB_m}}$: lowpass effect of the magnet itself (losses)
    - $T_{\mathrm{VtoI,circuit}}$: admittance of the circuit (higher L, lower current noise)

Voltage noise of Power Converters

- Allowed limits for single tones (all new HL-LHC PCs) [1]:



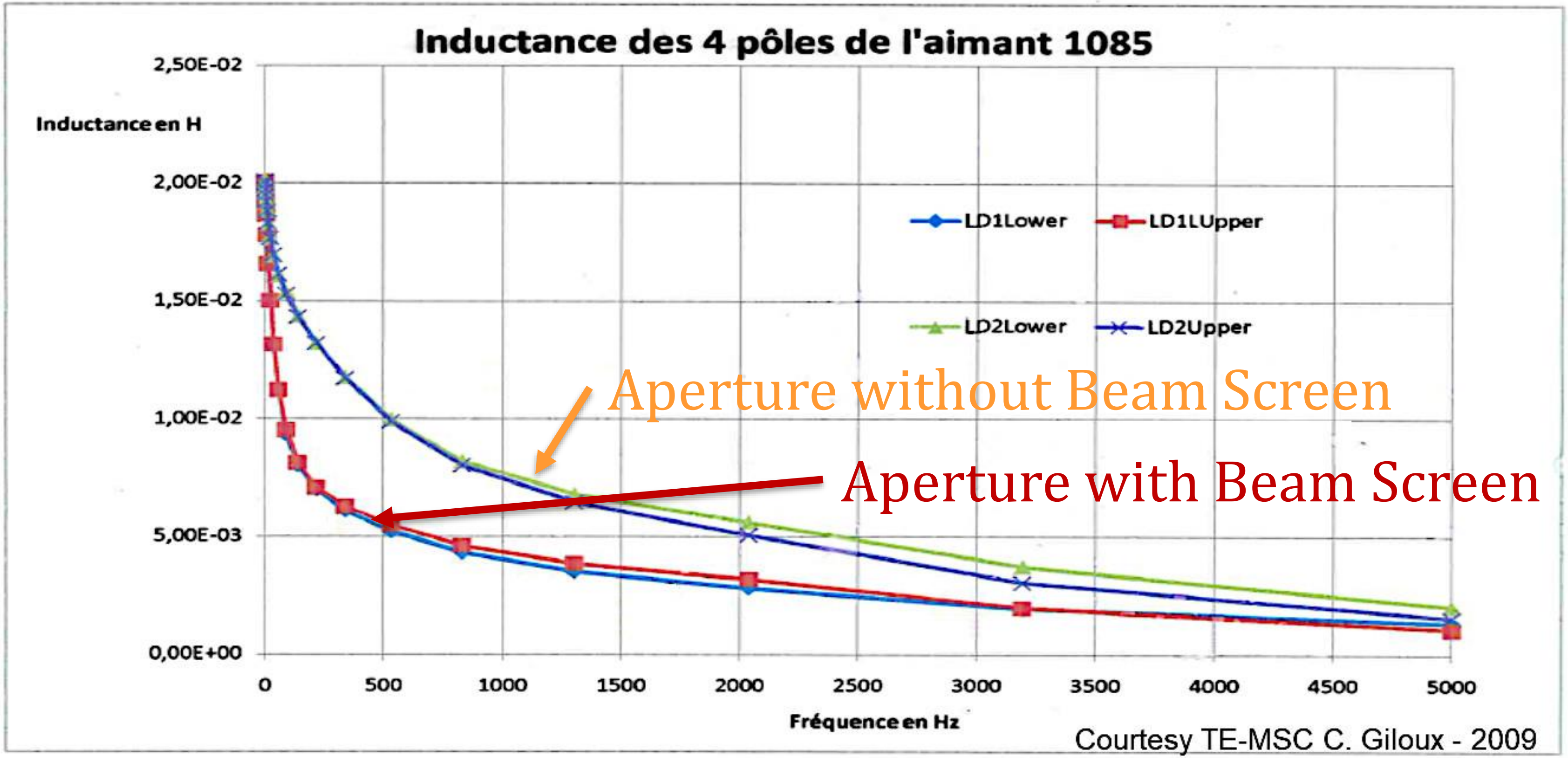
SC magnets from PC noise “perspective”



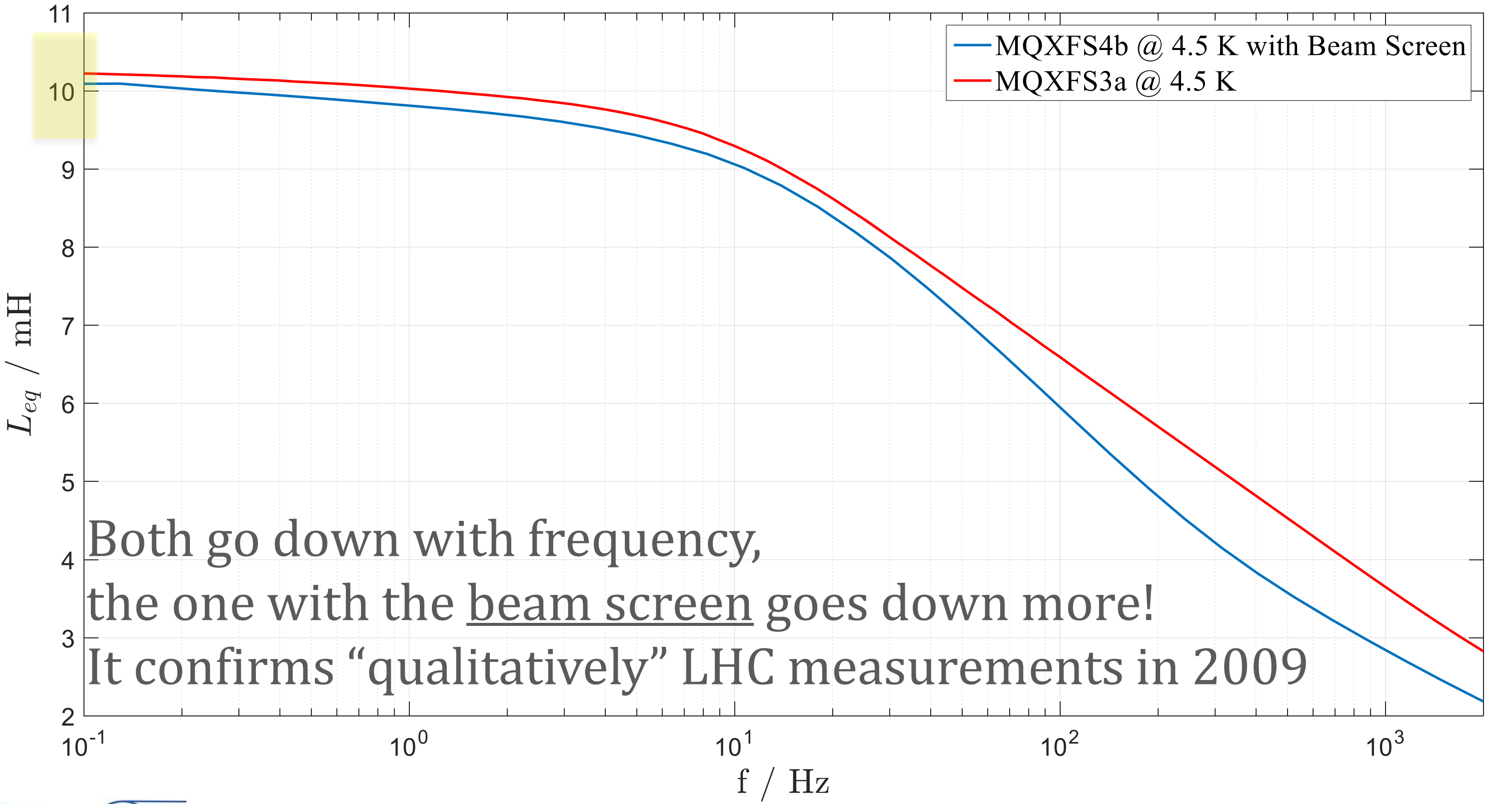
$$\text{Equivalent inductance}: \ L_{eq}(f) = \frac{Z_{magnet}(f)}{j2\pi f}$$

$\text{N. B.}:$ focus on small signal regime around a given DC current

“Equivalent Inductance” of LHC Dipole at 1.9 K



"Equivalent Inductance" of MQXFS @ 4.5 K



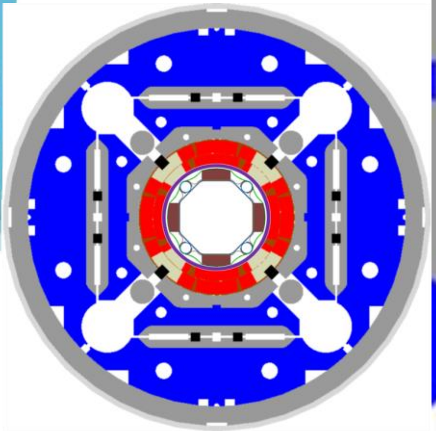
Both go down with frequency,
the one with the beam screen goes down more!
It confirms "qualitatively" LHC measurements in 2009

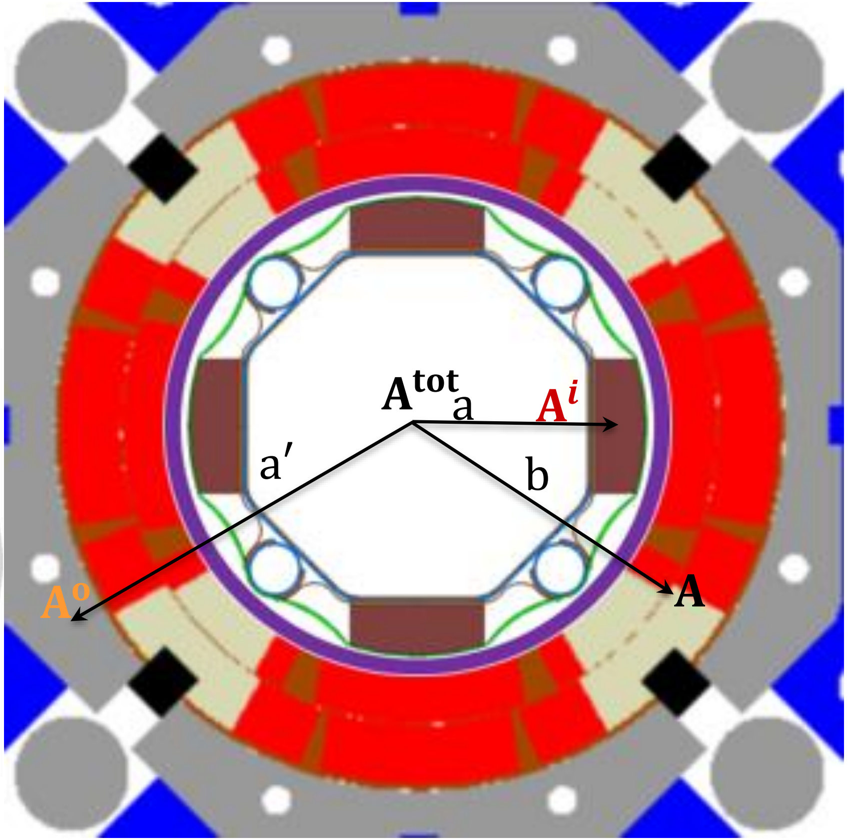
Modelling

Dynamic modelling of SC magnets

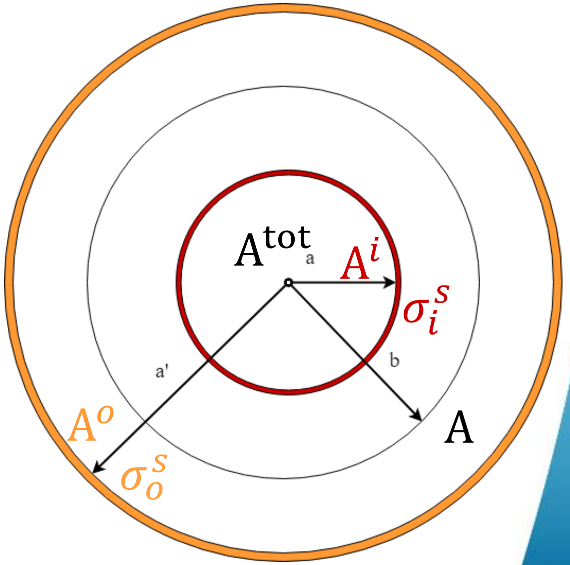
- Basically two loss mechanisms: beam screen and outer shell

$$A^{tot} = A + A^{i} + A^{o}$$



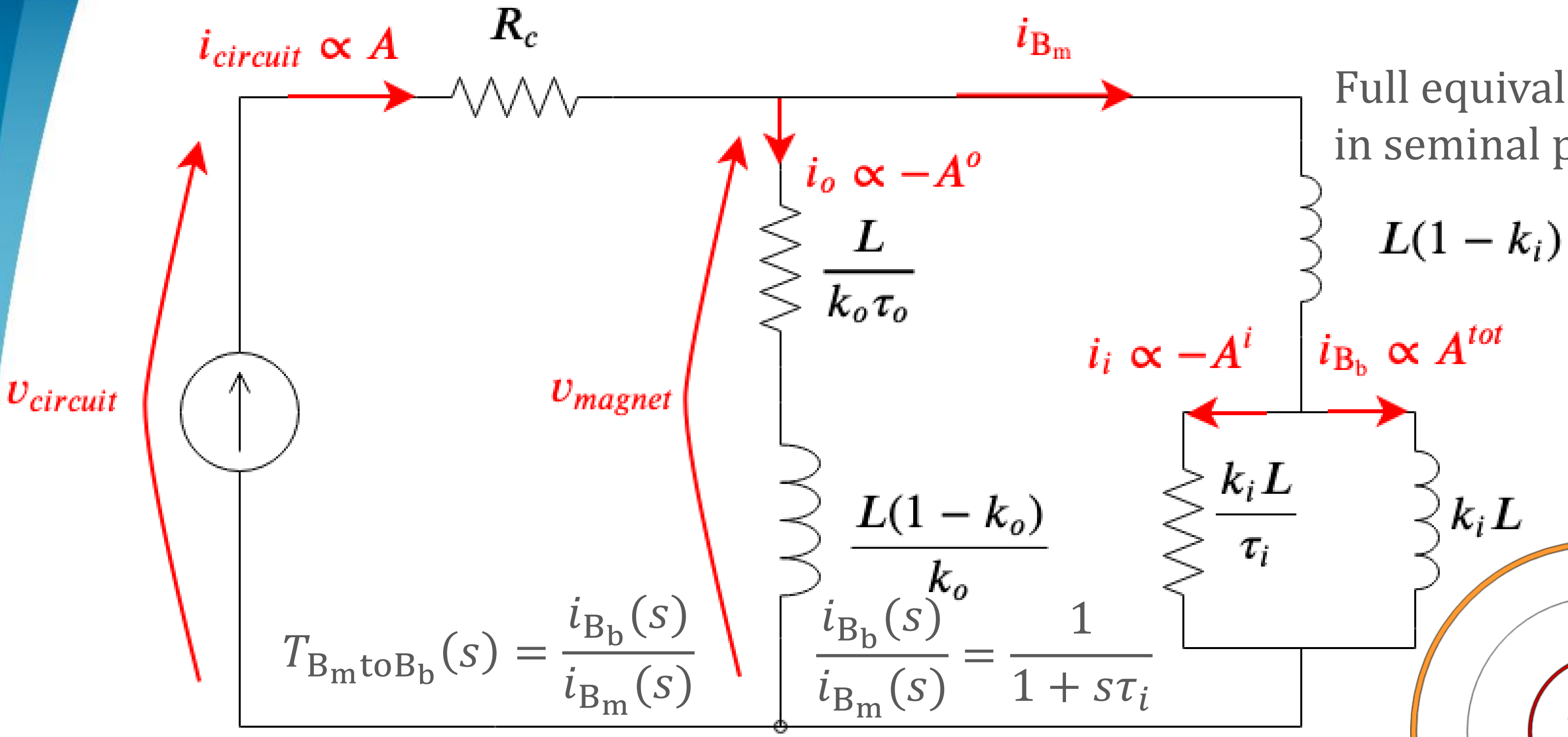


Analytical solutions exist for infinitely-thin conductive shells. Fermilab TM-991[2]
Robert E. Shafer - 1980



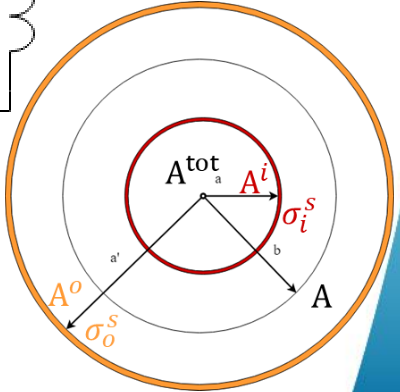
Equivalent Circuit: "Shafer modelling" at 1st order

Full equivalent circuit not in seminal paper TM-991

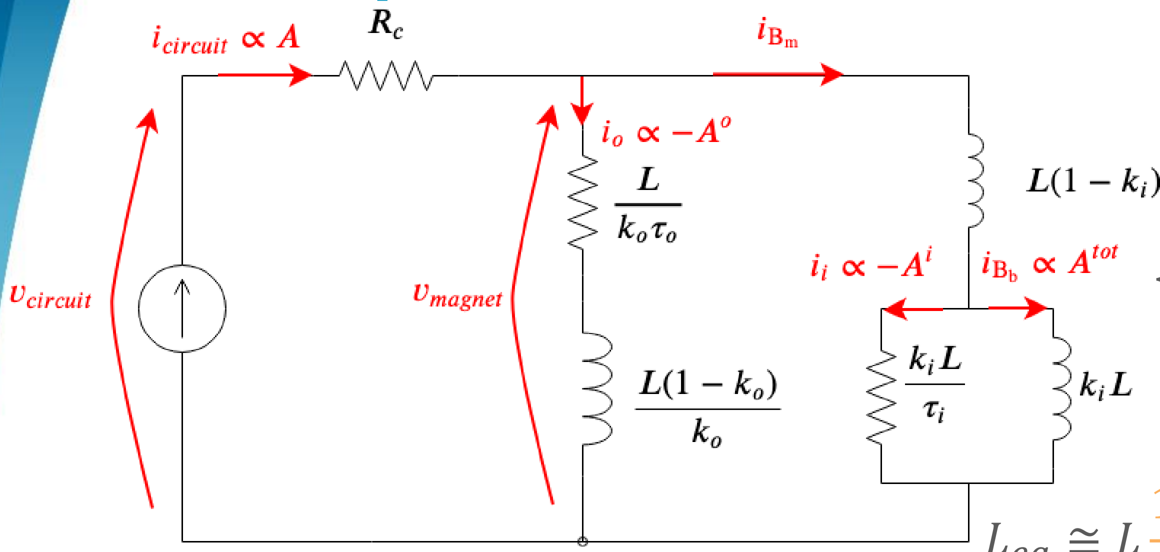


$$T_{B_m to B_b}(s) = \frac{i_{B_b}(s)}{i_{B_m}(s)} \qquad \frac{i_{B_b}(s)}{i_{B_m}(s)} = \frac{1}{1+s\tau_i}$$

$$k_i = \left(\frac{a}{b}\right)^{2n} \quad k_o = \left(\frac{b}{a'}\right)^{2n} \qquad \tau_i = \frac{2n}{\mu_0 2\pi \sigma_i^s a} \qquad \tau_o = \frac{2n}{\mu_0 2\pi \sigma_o^s a'}$$



From equivalent circuit to B-field "seen by the beam"



$$\begin{cases} \tau_o' = \tau_o(1-k_o) & \text{Magnet losses} \\ \tau_i' = \tau_o(1-k_i) & \text{Beam Screen} \\ \tau = L/R_c & \text{Circuit nominal} \end{cases}$$

$$L_{eq} \cong L \frac{1+s\tau_o(1-k_o)}{1+s\tau_o} \frac{1+s\tau_i(1-k_i)}{1+s\tau_i}$$

$$L_{eq} = L \frac{[1+s\tau_o(1-k_o)][1+s\tau_i(1-k_i)]}{1+s(\tau_i+\tau_o)+s^2\tau_i\tau_o(1-k_ik_o)}$$

Additional 1st order lowpass filtering but weaker than $\mathrm{B_b}/\mathrm{B_m} = i_{\mathrm{B_b}}/i_{\mathrm{B_m}}$

$$\frac{\mathrm{B_b}(s)}{V_{circuit}(s)} = \frac{K}{R_c} \frac{1+s\tau_o'}{1+s(\tau+\tau_i+\tau_o)+s^2[\tau(\tau_i'+\tau_o')+\tau_i\tau_o(1-k_ik_o)]+s^3\tau\tau_i\tau_o}$$

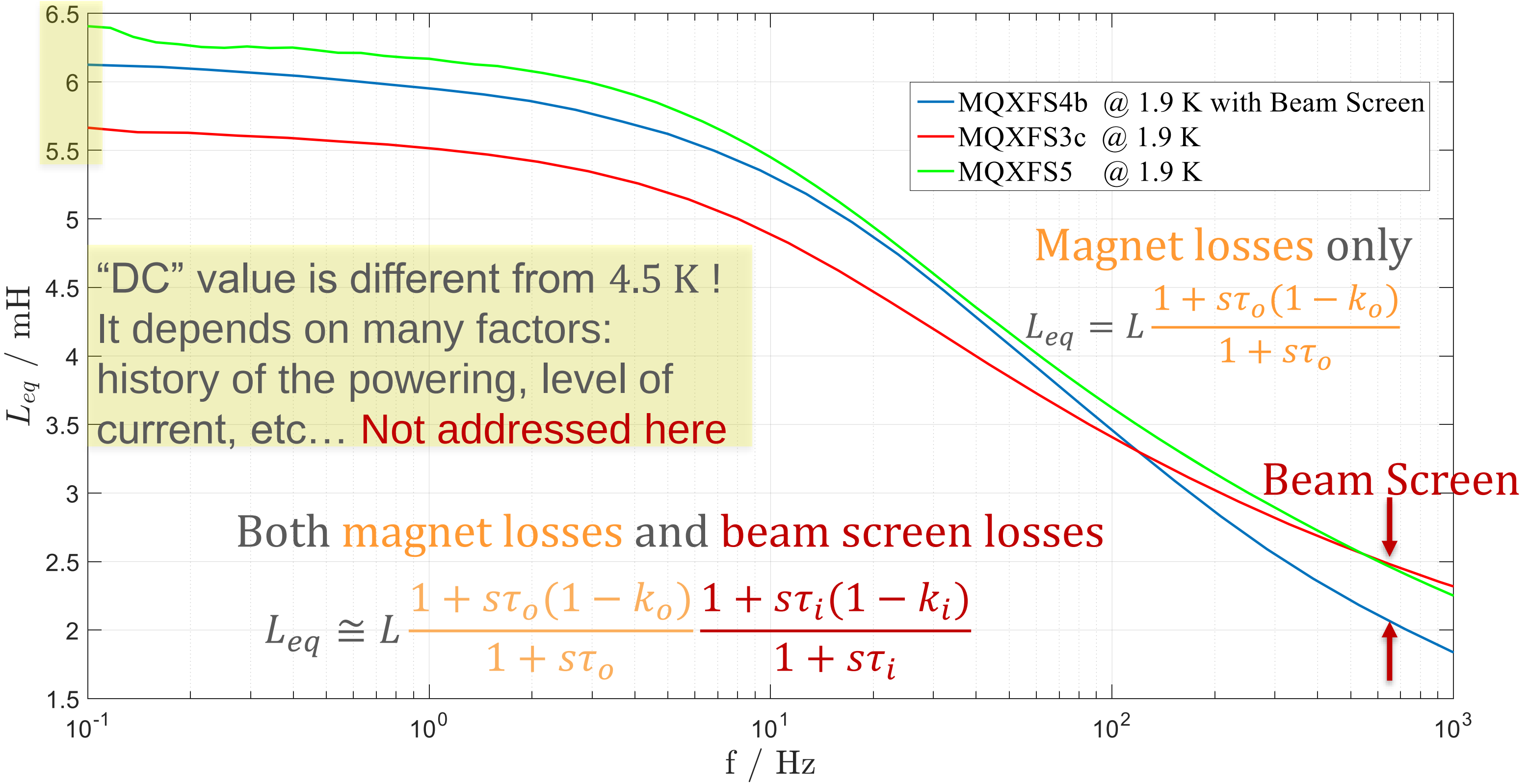
Simple R-L series model currently considered by WP2 to date

$$\frac{\mathrm{B_b}(s)}{V_{circuit}(s)} \cong \frac{K}{R_c} \frac{1}{1+s\tau} \frac{1}{1+s\tau_i(1-k_i)}$$

Experimental Results

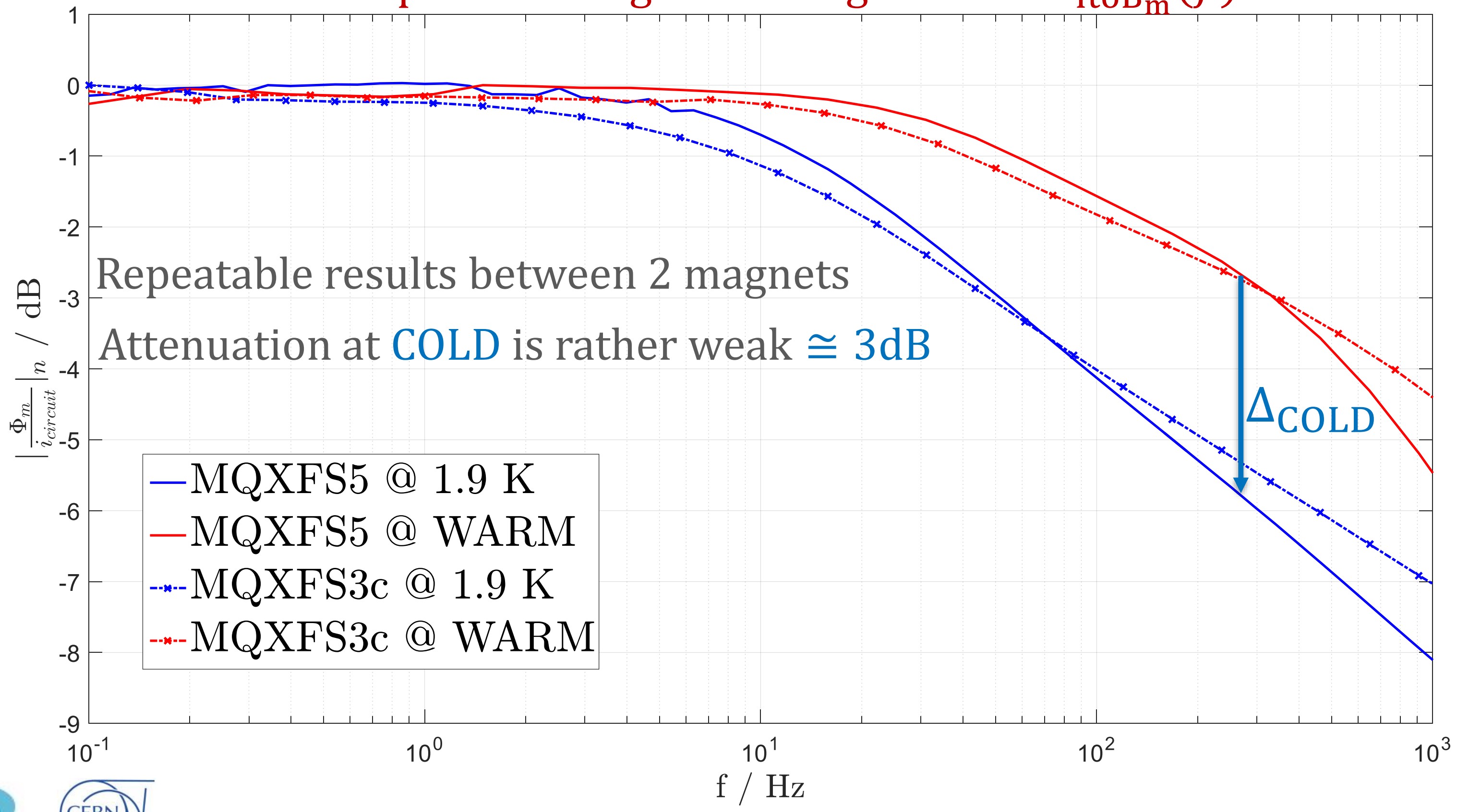
Equivalent Inductance: more experimental results

Observed behavior in excellent qualitative agreement with the model !

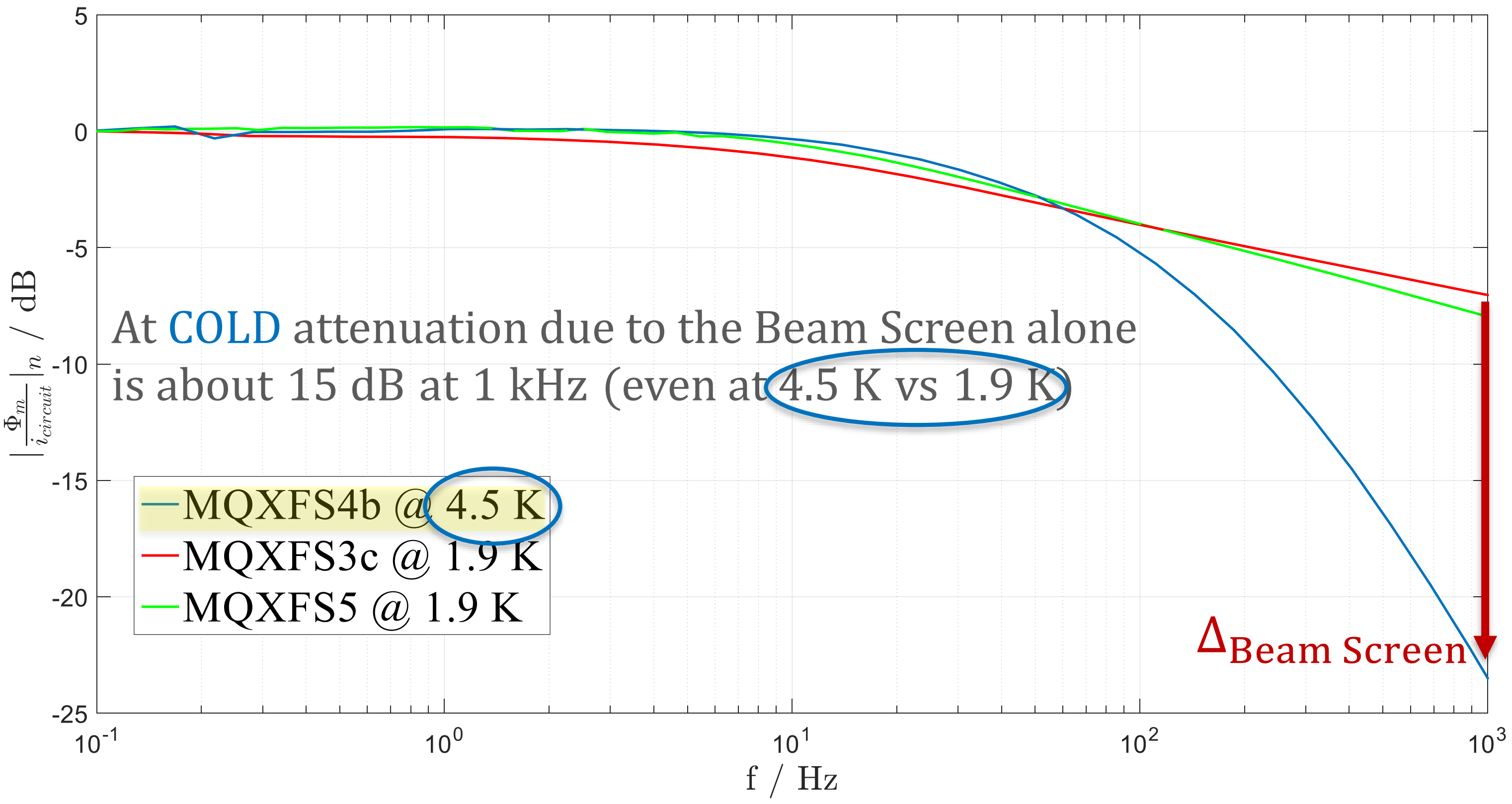


Measured Magnetic Flux / Current vs Frequency

"Weak" lowpass filtering of the magnet itself $T_{\mathrm{ItoB_m}}(f)$

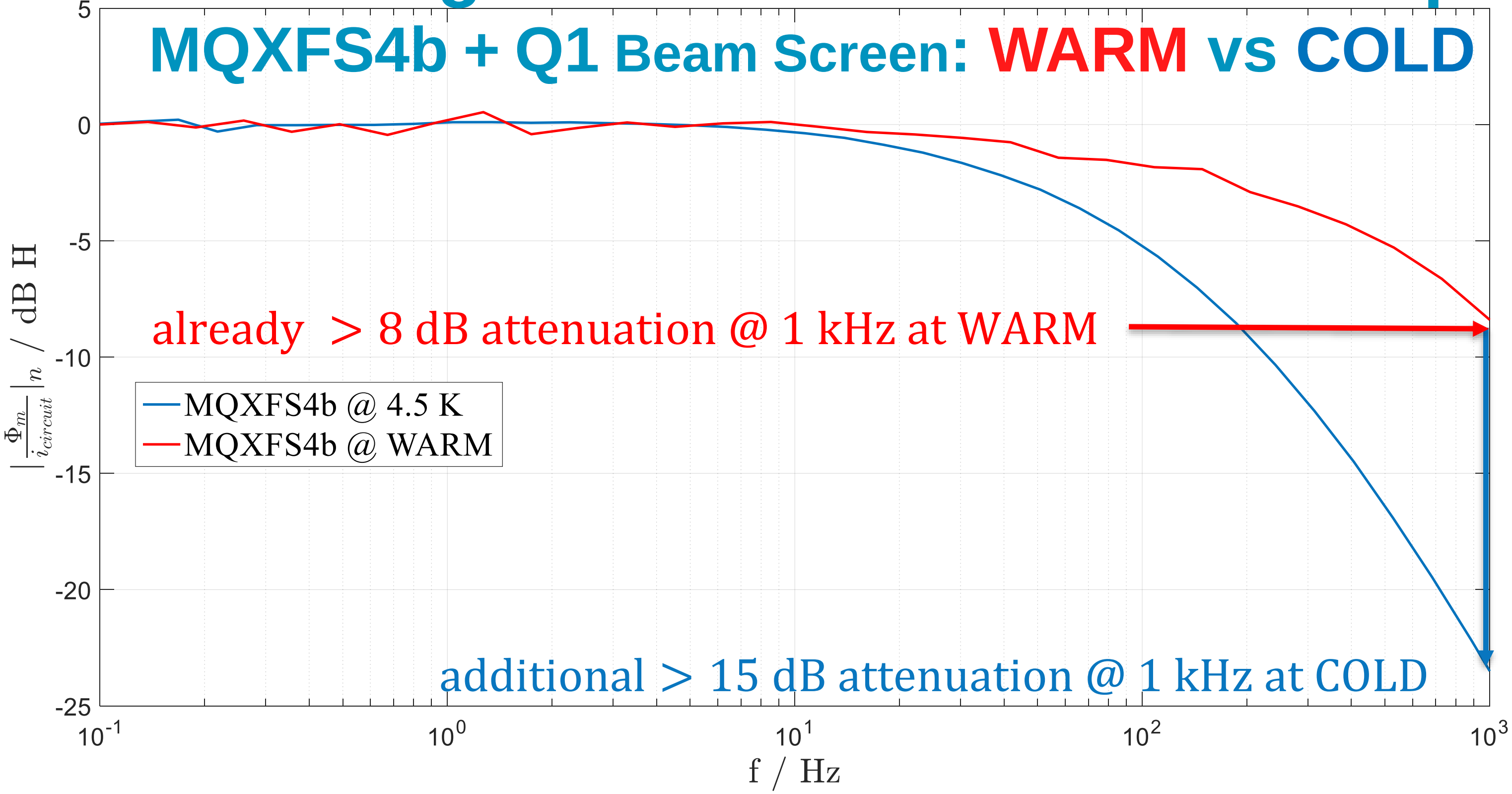


Measured Magnetic Flux / Current vs Frequency



Measured Magnetic Flux / Current vs Frequency

MQXFS4b + Q1 Beam Screen: WARM vs COLD



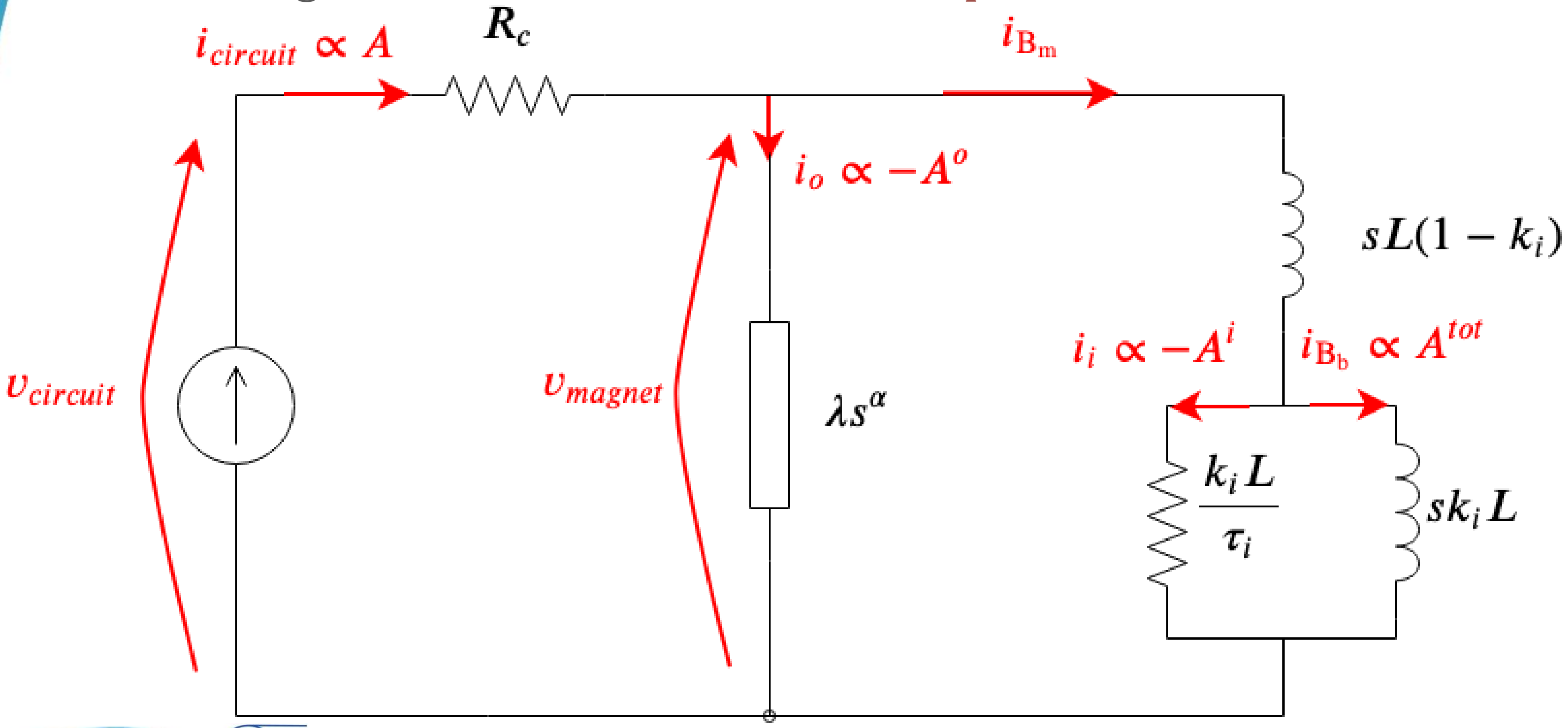
At COLD both magnet losses and beam screen losses help attenuating “**field noise**” !

Beam Screen: Shafer modelling at 1st order

Magnet/Beam Screen LHC @ 20 K, HL-LHC @ 80 K	COMSOL	Analytical Model			
	PRAB[3]			non peer reviewed yet	
	$\tilde{f}_i$ / Hz	$\hat{f}_i$ / Hz	$\hat{\tau}_i$ / ms	$\hat{k}_i$ /−	$\hat{f}_i/(1-\hat{k}_i)$ / Hz
LHC Dipole	106	99	1.61	0.72	354
LHC Quadrupole MagnetoResistance	145	139	1.14	0.52	290
D1	61.6	53.3	2.99	0.68	167
D2	44.5	46.3	3.44	0.59	113
Q1	31.8	31.2	5.10	0.36	48.8
Q2 − Q3	71.9	75.8	2.10	0.49	149
Q1 proto @ 1.9 K	19.1 NEW	17.5 NEW	9.09 NEW	0.36 NEW	27.3 NEW

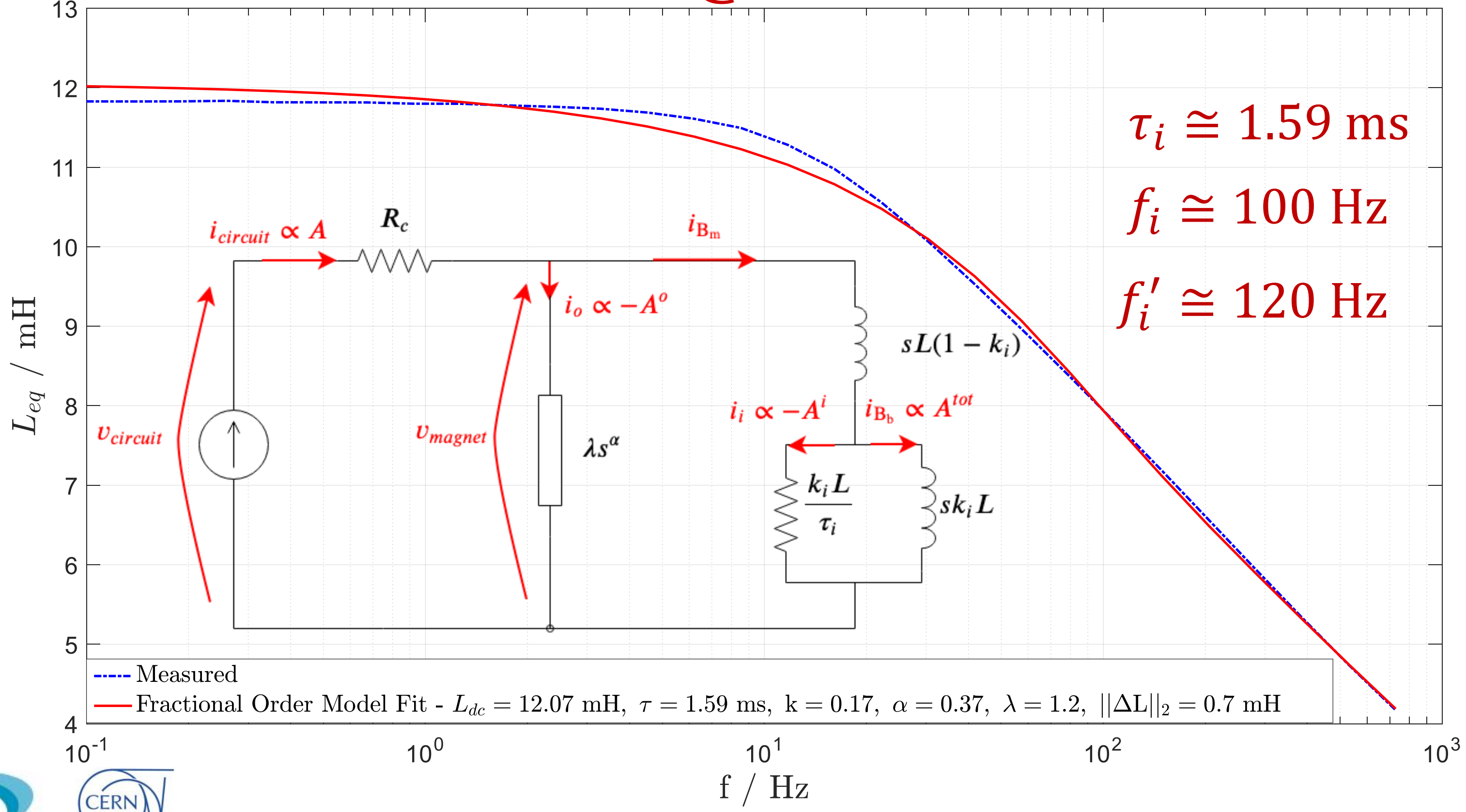
Experimental Results: Quantitative estimation

For magnet losses fractional order impedance model is needed



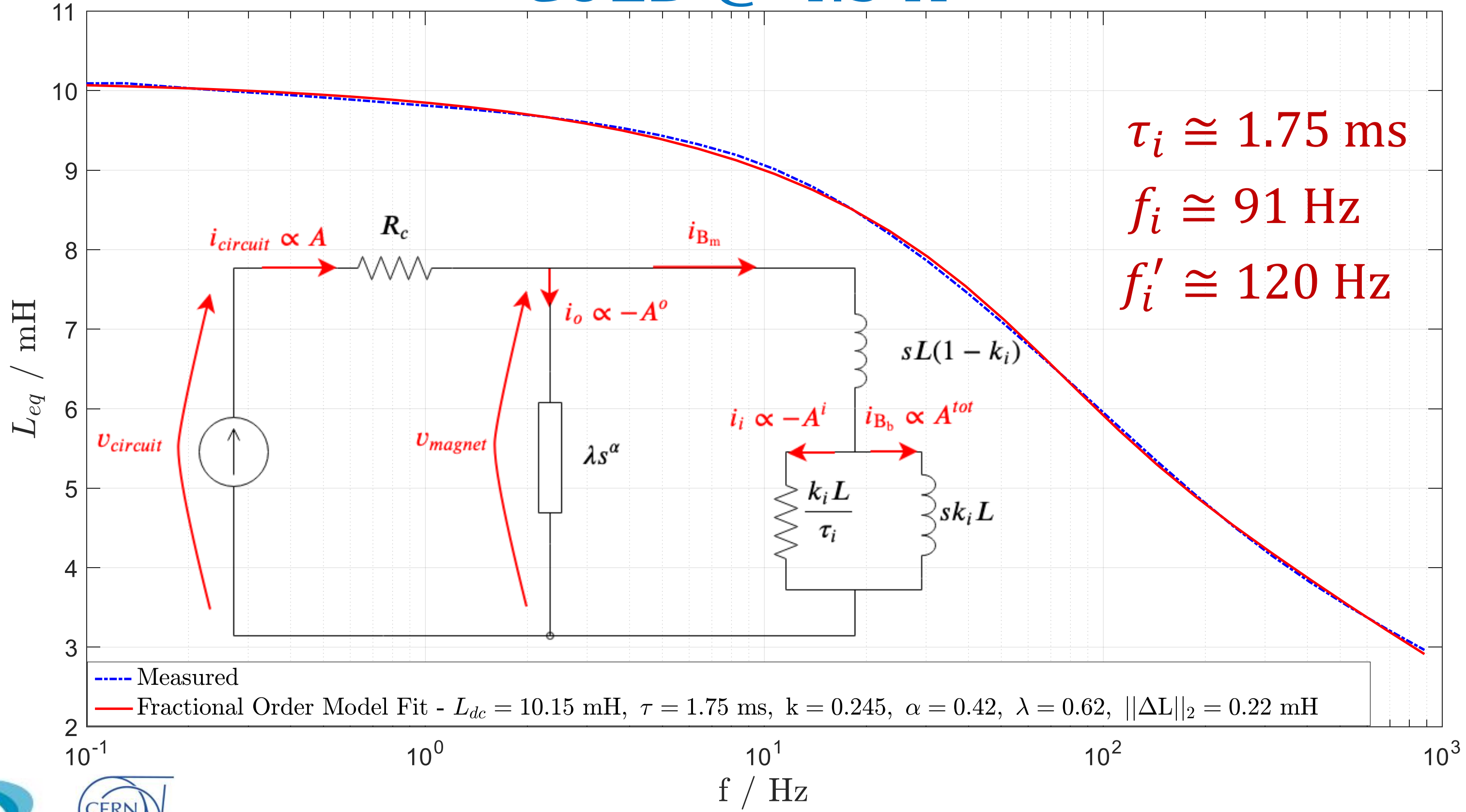
MQXFS4b with Q1 Beam Screen proto

WARM @ ≅ 95 K



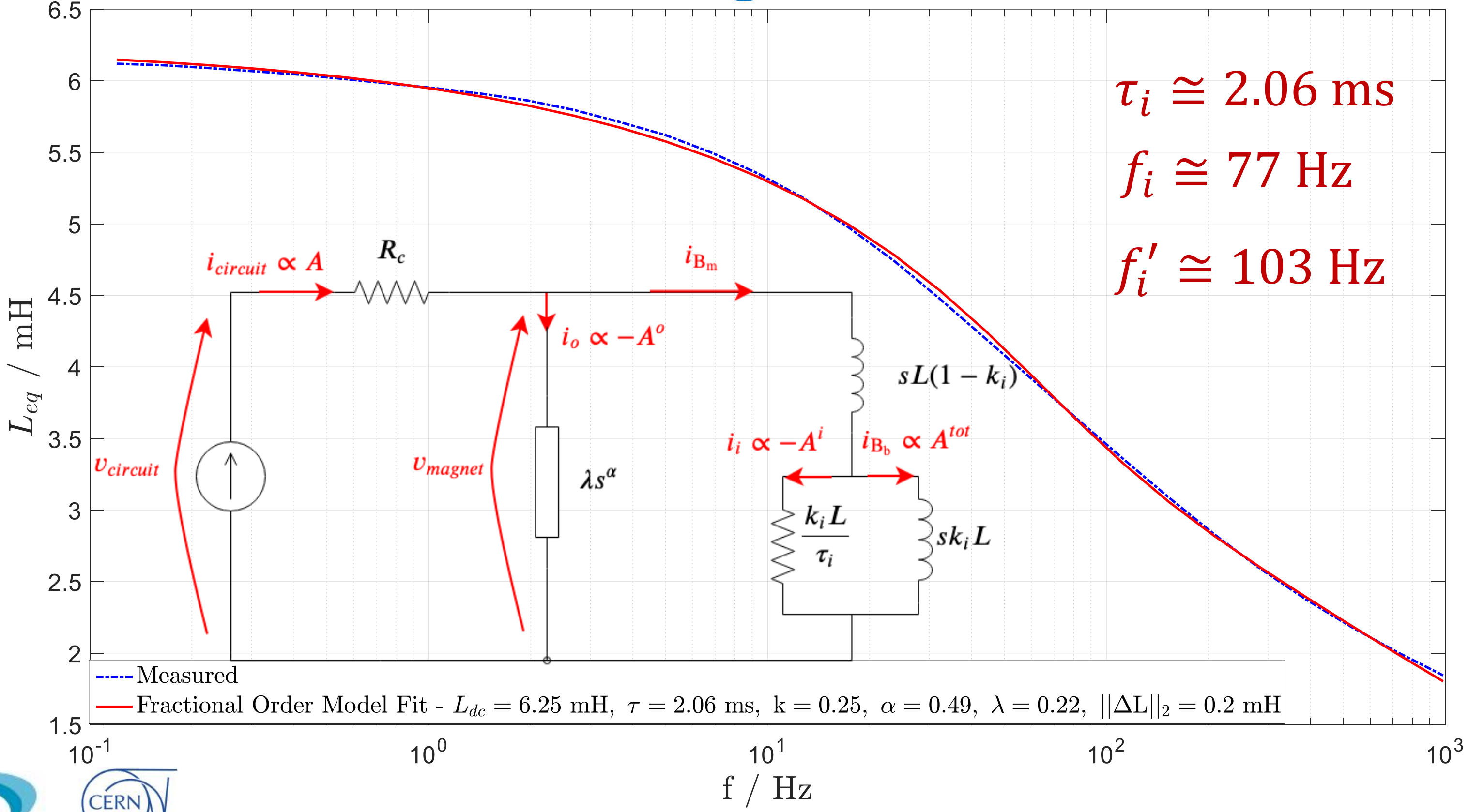
MQXFS4b with Q1 Beam Screen proto

COLD @ 4.5 K



MQXFS4b with Q1 Beam Screen proto

COLD @ 1.9 K



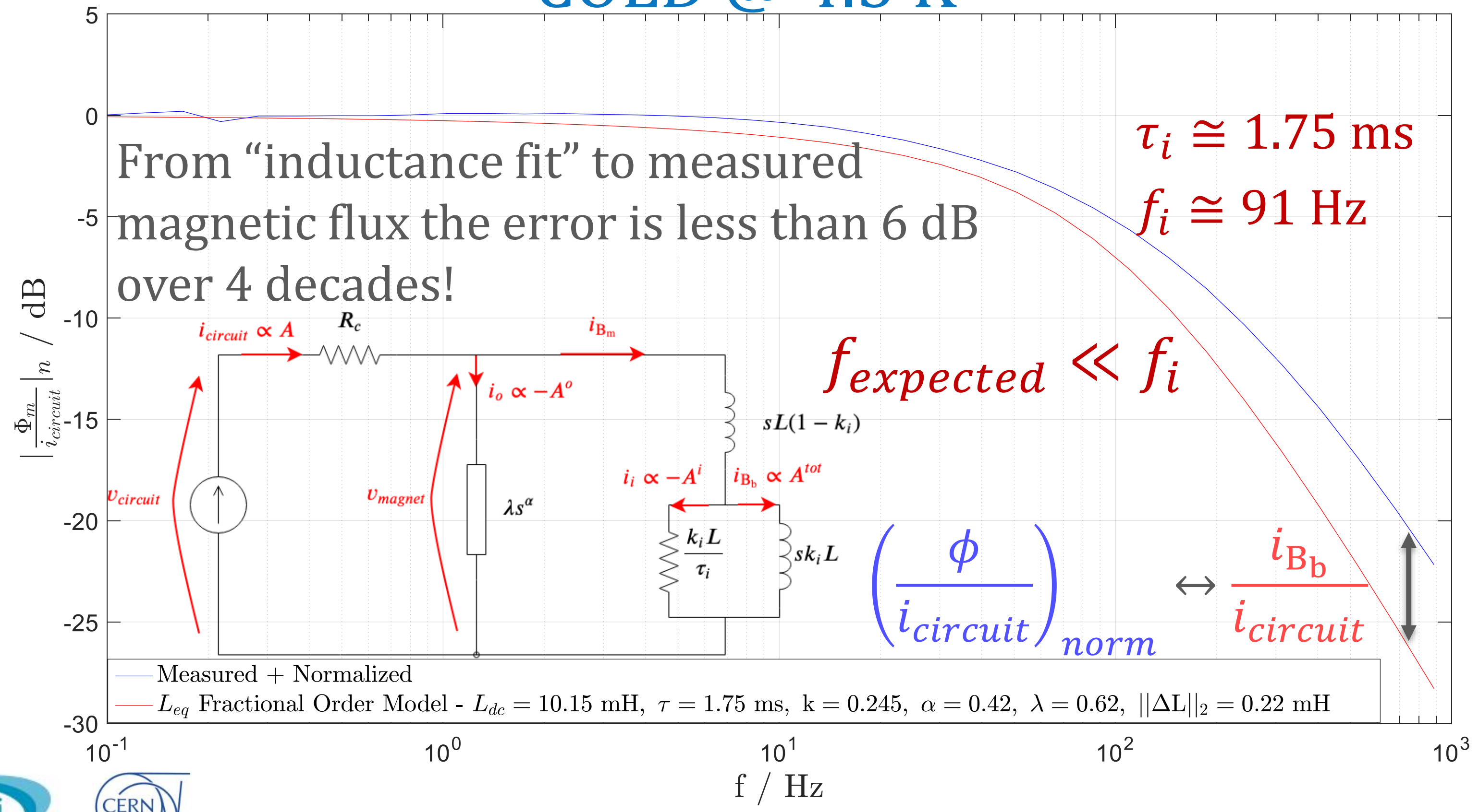
$\tau_i \cong 2.06$ ms

$f_i \cong 77$ Hz

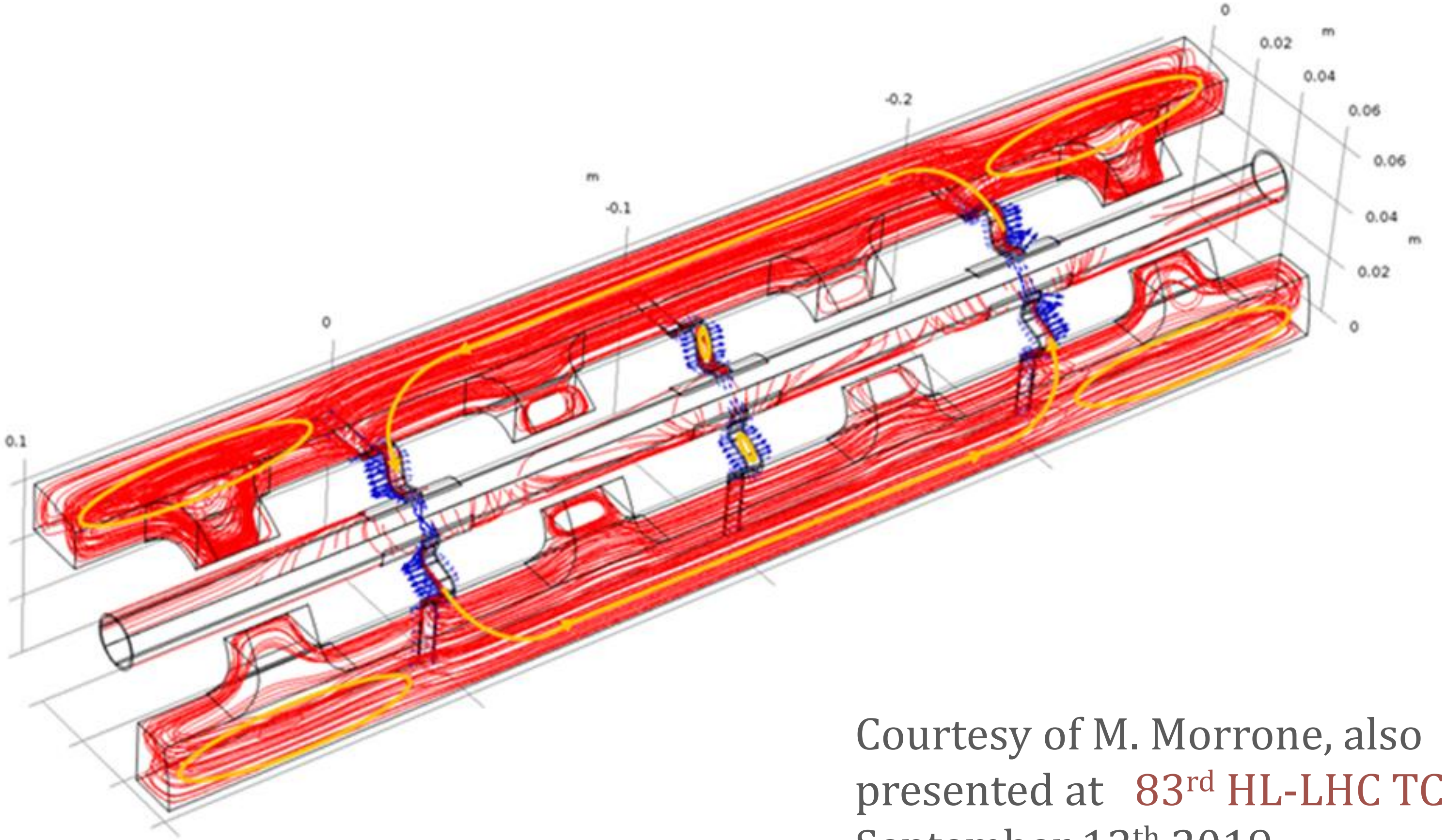
$f_i' \cong 103$ Hz

MQXFS4b with Q1 Beam Screen proto: from v,i to ϕ

COLD @ 4.5 K



Q1 Beam Screen Proto – 3D



Courtesy of M. Morrone, also presented at 83rd HL-LHC TCC September 12th 2019

Some preliminary conclusions

- Lowpass filtering due to magnet losses at nominal current unknown
- Lowpass filtering of the Beam Screen is dominant anyway:
  - at nominal current Magneto Resistance improves accuracy only slightly
  - Extra lowpass filtering from Voltage to B-field is weaker than B-field to B-field (or circuit current to B-field)
    - it depends also on the relative (equivalent) dimensions of the beam screen with respect to the magnet aperture – model parameters still need full validation
    - effects are explored up to few kHz (presented up to 1 kHz)
  - Above few kHz stray or parasitic effects MUST be considered !
  - Large discrepancy of Q1 beam screen proto needs to be understood
- These models can already be useful to WP2 for noise estimation

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Thank you for your kind attention

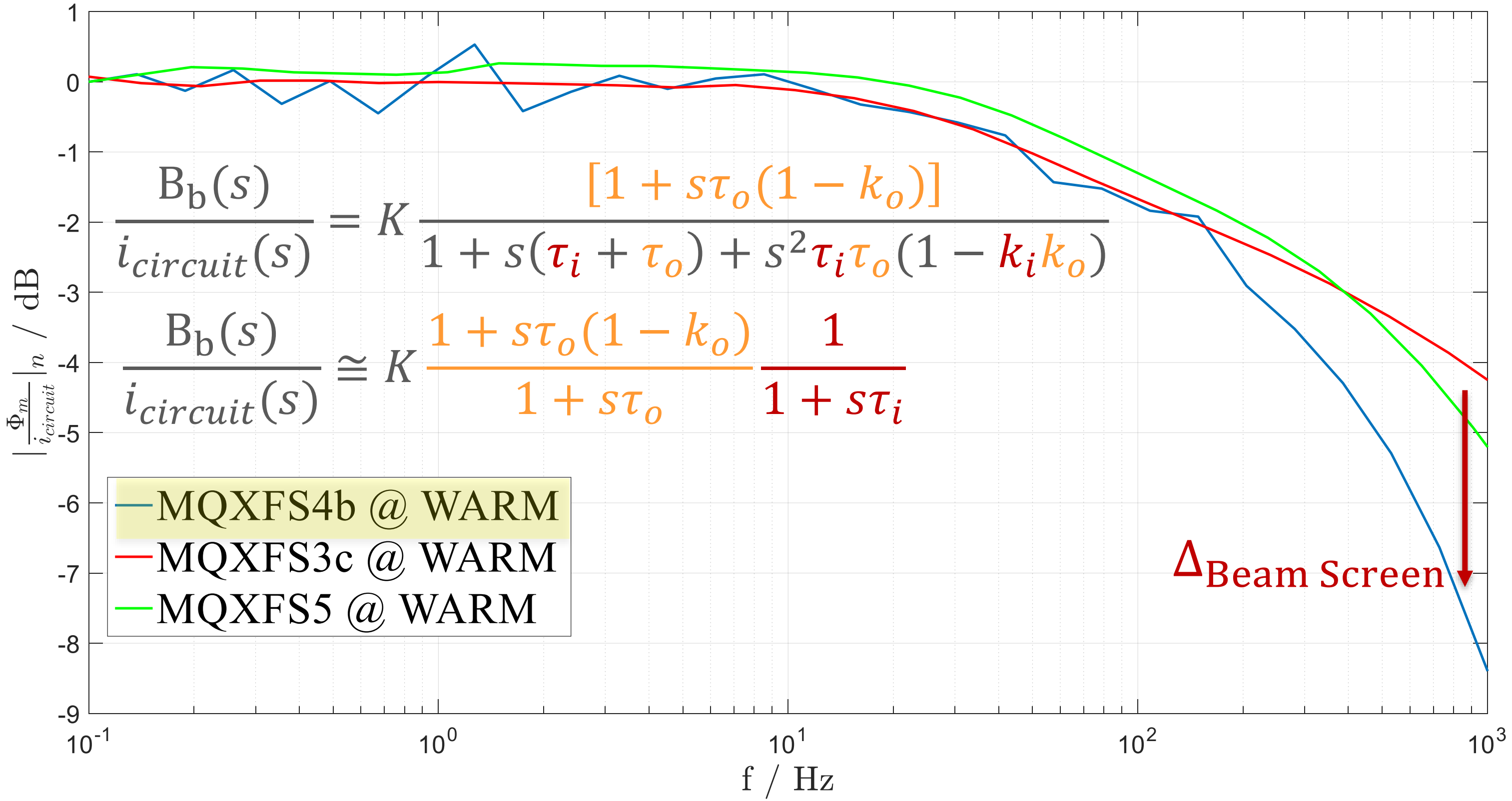
Credits to: S. Ierardi (WP6B), M. Morrone (WP12), L. Fiscarelli (TE-MSC), L. Bortot (TE-MPE)

References

[1] Update of beam dynamics requirements for HL–LHC electrical circuits, CERN-ACC-2019-0030, D. Gamba et al. – 2019
[2] Eddy Currents, Dispersion Relations, and Transient Effects in superconducting Magnets, FERMILAB TM-991, R. E. Shafer – 1980
[3] Magnetic frequency response of High-Luminosity Large Hadron Collider beam screens, PRAB, M. Morrone et al. – 2018

Additional Slides

Measured Magnetic Flux / Current vs Frequency



Q1 Beam Screen Proto - Summary

- **COMSOL simulations / analytical model:**
  - Cut – off frequency below 20 Hz @ 1.9 K (experimental conditions)
- **Experimental results - preliminary fit:**
  - Cut – off frequency of about 77 Hz @ 1.9 K (inferred by fitting L_{eq})
  - Cut – off frequency of about 91 Hz @ 4.5 K (inferred by L_{eq} and ϕ_{meas})
  - Large mismatch still unexplained
    - "Q1 type" beam screen is the one that fits less with 1st order Shafer model
    - But its lowpass filtering is supposedly stronger than 1st order not weaker
  - Maybe the cause is a large 3D vs 2D discrepancy because of thermal links