Measuring eddy current contributions in normal conducting magnets

Predicting and measuring Eddy currents is a challenging task

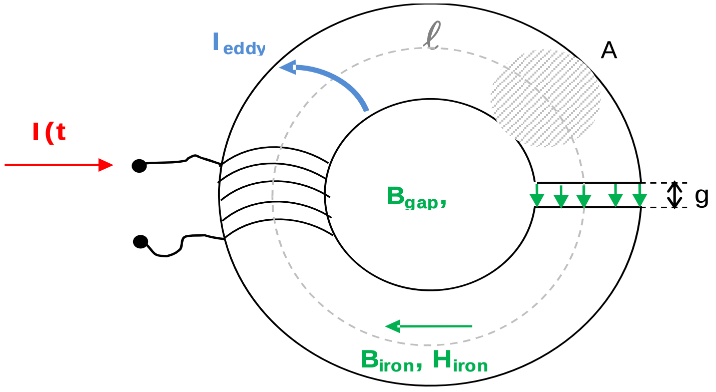
→ **Amplitude and time scale of eddy currents depend on:**

- Magnet geometry
- End plates geometry (3D calculation, very important for short magnets)
- Applied current ramp rate

→ **Hard to predict accurately, depending on uncertain parameters such as:**

- Microstructural and magnetic properties of the iron yoke (Quality control)
- Permeability and resistivity at a given current and temperature (Si steel, ...)
- Surface resistivity of the laminations (Manufacturing)
- Mechanical tolerances leading to unwanted air gaps in the magnetic circuit (Design)

Eddy current in a ideal magnet (linear, uniform flux in the gap, no leak)



From Faraday's theorem and flux conservation:

$$\begin{cases} H_{gap} g + H_{iron}(\ell - g) = NI \\ B_{gap} = \mu_0 H_{air} \\ B_{iron} = \mu_0 \mu_r H_{iron} \\ \Phi = B_{gap} A = B_{iron} A \end{cases} \quad \Rightarrow \quad B = B_{gap} = B_{iron}$$

Magnetic induction (no leakage):

$$B = \frac{\mu_0 \mu_r NI}{\ell + (\mu_r - 1) g}$$

E.M.F. driving eddy currents in the iron:

$$\varepsilon = -\frac{\partial \Phi}{\partial t} \propto -\frac{\mu_0 \mu_r A N \dot{I}}{\ell + (\mu_r - 1) g}$$

Resistance of eddy current's path:

$$R = \rho \frac{l_{path}}{S_{\_path}} \propto \rho \frac{\sqrt{A}}{\ell \sqrt{A}} \propto \frac{\rho}{\ell}$$

Eddy currents (assuming them so small as not to perturb the main field):

$$I_{eddy} = \frac{\varepsilon}{R} \propto \frac{\mu_0 \mu_r A N \dot{I}}{\rho \left(1 + (\mu_r - 1)\frac{g}{\ell}\right)}$$

Induction due to I_{eddy} (from Faraday's theorem + flux conservation, taking into account a geometric factor γ):

$$B_{eddy} = \gamma \frac{\mu_0 \mu_r N I_{eddy}}{\ell + (\mu_r - 1) g}$$

Total induction (assuming a linear ramp):

$$B_{TOT} = B - B_{eddy} = \frac{\mu_0 \mu_r N}{\ell + (\mu_r - 1) g} \left\{ I(t) - \gamma \frac{\mu_0 \mu_r A N}{1 + (\mu_r - 1)\frac{g}{\ell}} \frac{\dot{I}}{\rho} \right\} = \frac{\mu_0 \mu_r N \dot{I}}{\ell + (\mu_r - 1) g} (t - \tau)$$

<u>Time lag</u> due to the eddy currents: $$\Delta\tau = \frac{\gamma}{\rho} \frac{\mu_0 \mu_r A}{1 + (\mu_r - 1)\frac{g}{\ell}}$$

Assuming moreover: $\mu_r >> 1$, $\mu_r >> \ell / g$:

$$B \approx \frac{\mu_0 \mu_r N I}{g}$$

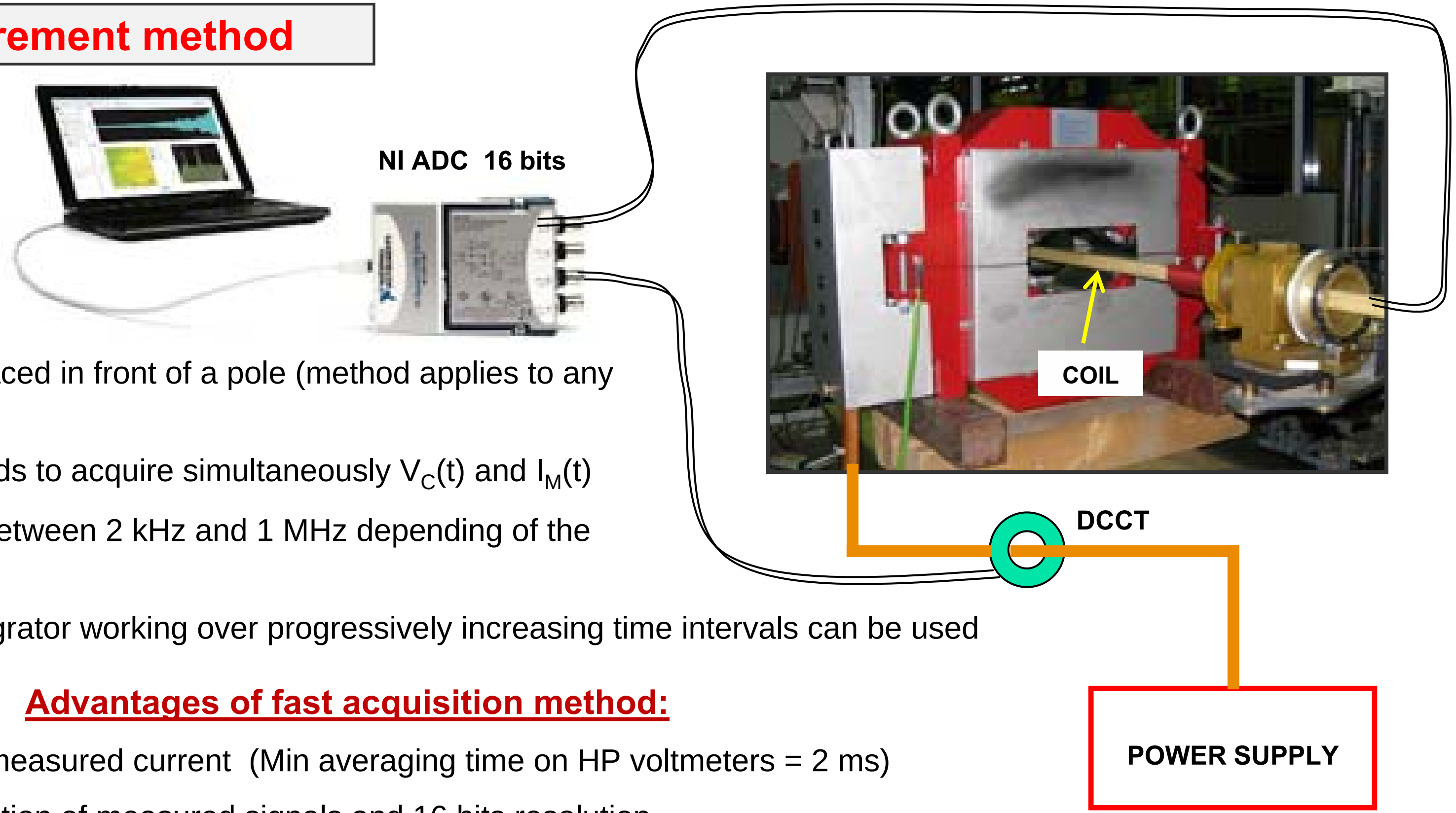
$$\boxed{\Delta\tau = \frac{\gamma}{\rho} \frac{\mu_0}{g} \ell A}$$

Iron yoke volume

Resistivity

Gap

Measurement method



- Fixed integral coil placed in front of a pole (method applies to any multipole order)
- High-speed ADC cards to acquire simultaneously $V_C(t)$ and $I_M(t)$
- ADC sampling rate between 2 kHz and 1 MHz depending of the current ramp up speed
- Alternatively, an integrator working over progressively increasing time intervals can be used

Advantages of fast acquisition method:

- No averaging of the measured current (Min averaging time on HP voltmeters = 2 ms)
- Accurate synchronization of measured signals and 16 bits resolution.
- Good time resolution (Limitation from DCCT bandwidth, typically 10 kHz)
- Fast implementation and portability (USB cards)
- Works indifferently with calibrated coils (in terms of B) or uncalibrated coils (in terms of flux Φ)

BUT: proper signal shielding, stray capacitance effects, cross-talk in the acquisition system must be kept under control at high frequency !

Example of results

Coil voltage (Vc) scaling ratio k

- Relation between magnet current and coil voltage:

$$I_B(t) = k\int_{t_0}^{t} V_C(t)dt$$

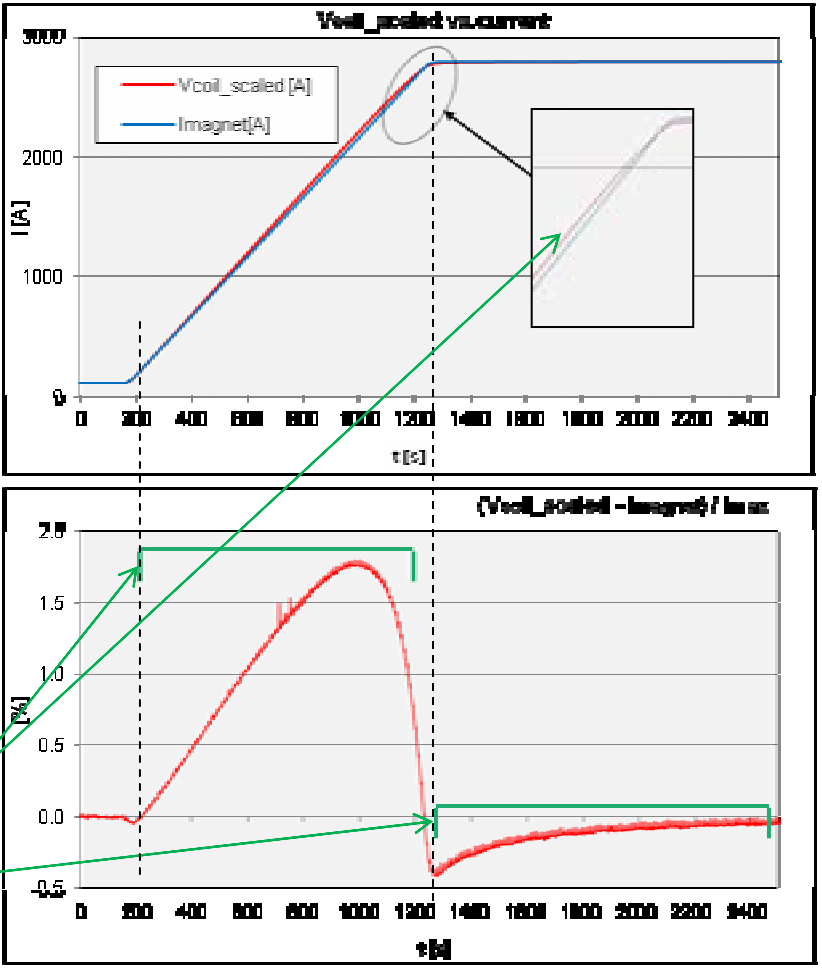
- The scaling ratio k is computed when transient effects are estimated to have died out:

$$k = \frac{I_M(t_1)}{\int_{t_0}^{t_1} V_C(t)dt}$$

Typical results with scaling ratio applied

- Field in apparent advance vs. current during ramp-up due to magnet's non-linearitiy (Saturation)

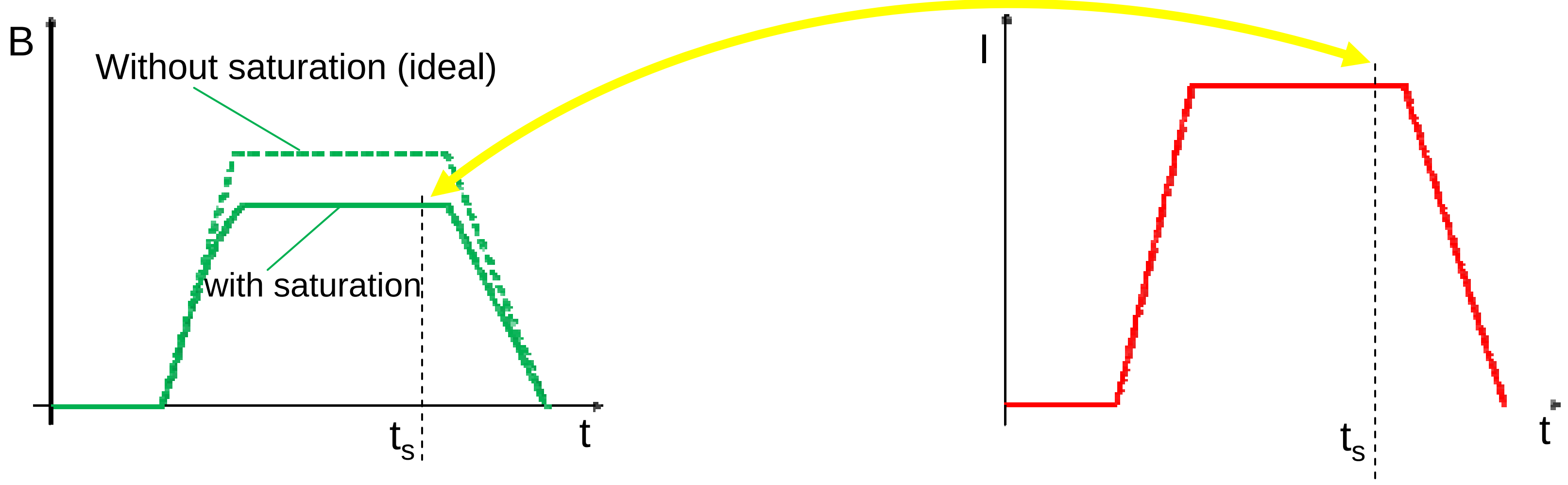
- Eddy currents effects on flat-top



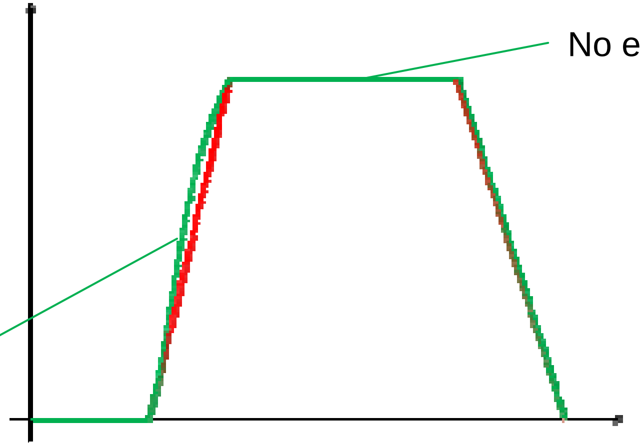
Information about eddy currents is contained in the difference $\frac{\Delta I}{I} = I^{*} - I_{m}$

Comparing I(t) vs. B(t), non-linear case, no eddy currents

Scale so that the curves coincide at the end of the flat-top



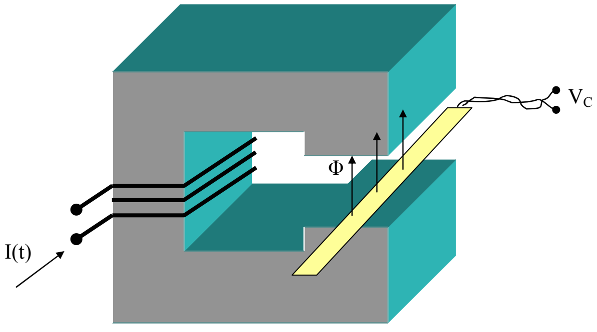
$$I^*(t) = \frac{I(t_s)}{B(t_s)} B(t)$$

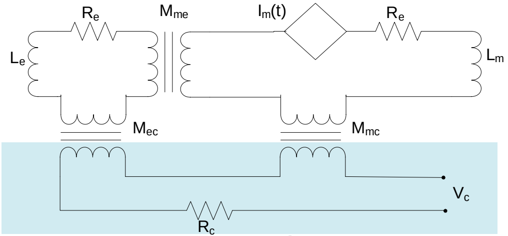


No eddy currents → $I^* \equiv I$

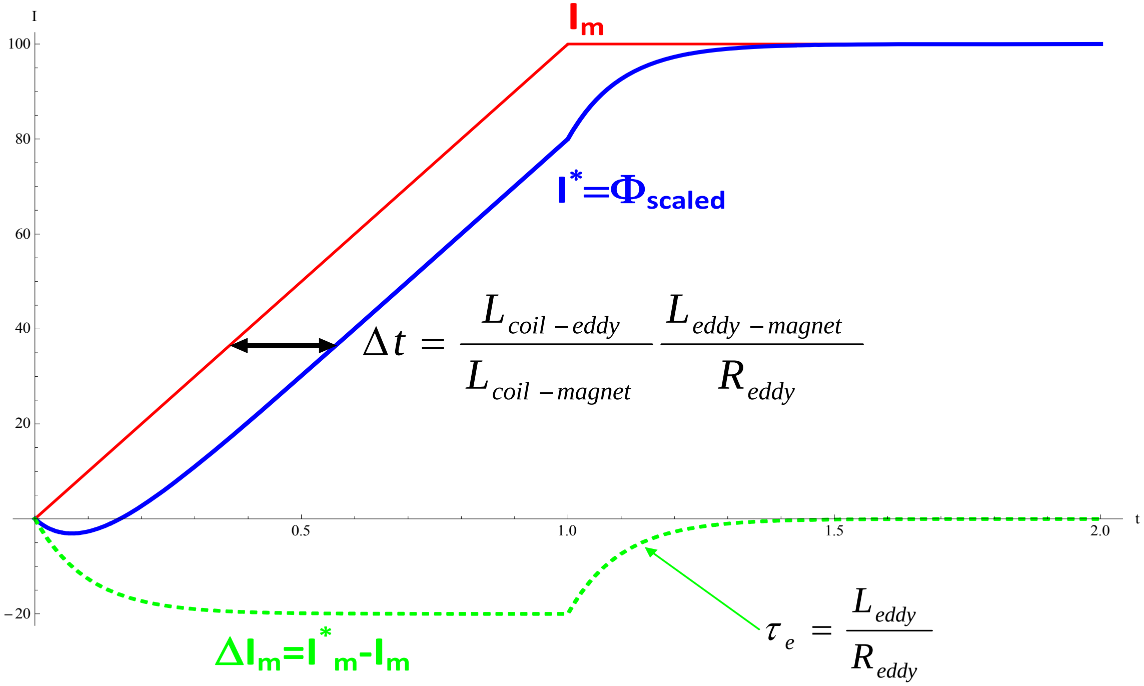
Apparent field advance due to the scaling procedure

Eddy current in a linear magnet – circuital model with variable coil position





See G.Golluccio, IMMW 16



$$\Delta t = \frac{L_{coil-eddy}}{L_{coil-magnet}} \frac{L_{eddy-magnet}}{R_{eddy}}$$

$$\tau_e = \frac{L_{eddy}}{R_{eddy}}$$

The decay time of the eddy currents depends only on the magnet

The field lag seen during the ramp and amplitude of the effect depend on the placement of the flux coil

Results on 15 magnet – Deducing a predictive law ?

Name	TYPE	Flat-top [A]	B max	dI/dt [A/sec]	dB/dt dG/dt	Rise time [s]	Ƭ Eddy current effect [s]	Amplitude Eddy current effect [%]	Metal sheet thickness [mm]	Gap or radius [mm]	Width [m]	Length [m]	Volume/gap	Aspect/ratio	Ƭ/ rise time
BOOSTER	dipole	5515	1.12	30000	6.09	0.18	0.053	0.140	0.8	70	0.71	1.54	0.78	45.5	0.29
CNAO MBS07	dipole	2800	1.5	2500	1.34	1.12	0.650	0.280	0.8	64	0.96	1.68	1.55	38.1	0.58
CNAO MBS02	dipole	2800	1.5	7000	3.75	0.40	0.390	0.770	0.8	64	0.96	1.68	1.55	38.1	0.98
MBXWS-03	dipole	500	0.94	2000	3.76	0.25	0.049	0.019	1.5	63	0.87	1.50	1.14	42.0	0.20
eLHC Proto 1	dipole	1500	0.09	10000	0.60	0.15	0.033	0.300	1	40	0.26	0.40	0.03	100.0	0.22
SPS main dipole	dipole	4900	1.8	4500	1.65	1.09	0.182	0.035	1.5	52	0.82	6.22	4.18	8.4	0.17
L4 steerer proto2	dipole	15	0.002	36100	4.81	0.0004	0.000	0.007	0.17	113.5	0.1135	0.049	0.00	2316.3	0.00
CNAO main MB	dipole	2800	1.6	2000	1.14	1.40	1.400	1.000	0.6	66	0.40	1.5	0.24	44.0	1.00
SPS main quad	quadripole	1945	20	1300	13.37	1.50	0.325	0.040	1.5	88	0.74	3.00	1.64	29.3	0.22
Triumf BT10	quadripole	400	4.56	9000	102.60	0.04	0.036	0.570		75	0.60	0.43	0.15	174.4	0.81
406	quadripole	400	2.25	2000	11.25	0.20	0.036	0.420	0.65	73	0.85	0.13	0.09	570.3	0.18
L2 EM quad Type III	quadripole	300	23	600000	46000	0.0005	0.000	1.000		30	0.09	0.06	0.00	526.3	0.38
MedA MQZC proto	quadripole	444	4.15	889	8.31	0.50	0.020	0.120		170	0.17	0.31	0.01	543.1	0.04
CTF3 septum	septum	1975	0.245	1000	0.12	1.98	0.067	0.018		40	0.20	0.63	0.02	63.4	0.03
PS MTE	octupole	520	10670	28000	57453	0.02	0.018	0.600		70	0.77	0.41	0.24	171.6	0.97

→ **Theory says:**

- Time constant should be proportional to iron volume
- Time constant should be in inverse proportion to gap
- Amplitude should be proportional to dB/dt

→ **Results for the analysis of this 15 magnets → theory prediction not confirmed by measurements**

- Iron volume, gap and rise time are not predominant over other parameters
- End plates, permeability, resistivity, welded bars along the magnet have more influence on results.

Evolution of Eddy current with magnet saturation and dI/dt

Measurement parameters:

2 different flat-top

4065 A = linear range

5515 A = saturated

3 different current rise time

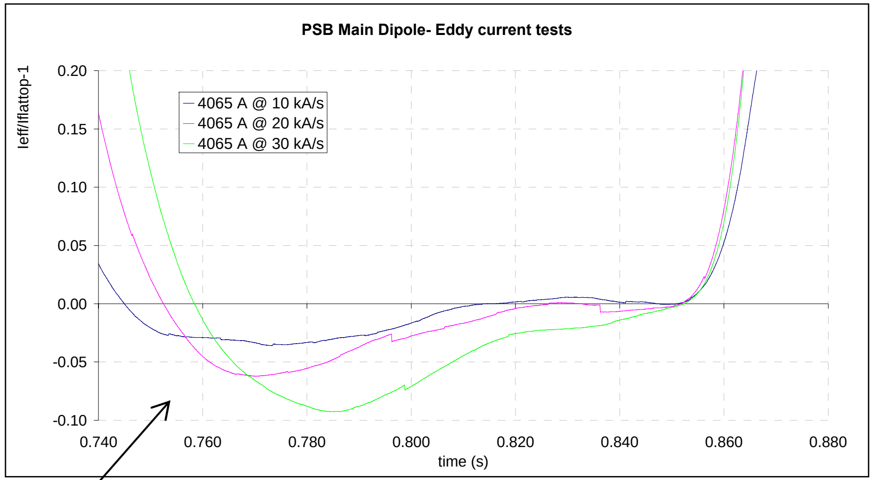
10 kA/s

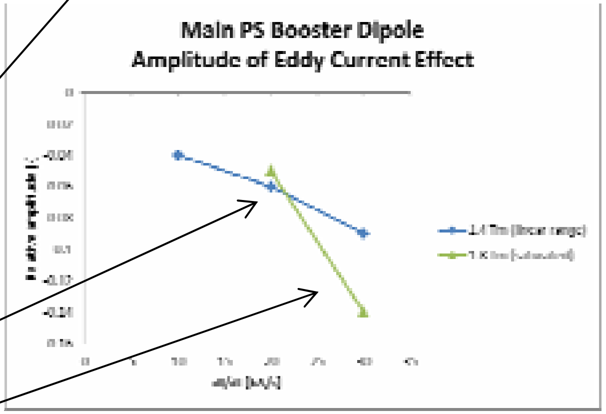
20 kA/s

30 kA/s

Results about Eddy currents:

- As predicted, time constant not rise-time dependant
- Relative amplitude <u>increases with rise time</u>
- Relative amplitude <u>increases with saturation</u>





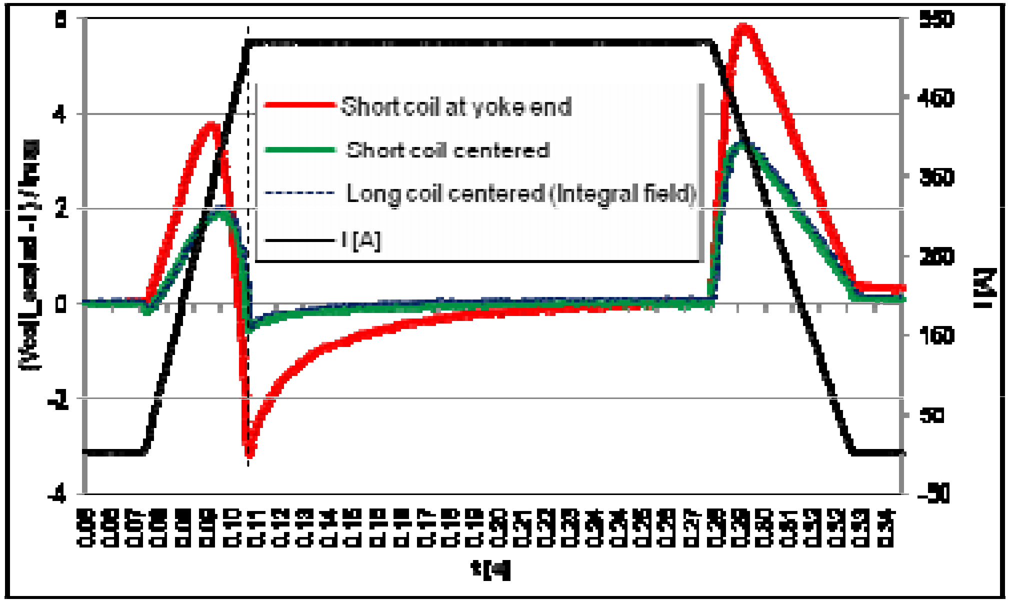
Eddy current over magnet length

Measuring locally Eddy current effects in magnet center and close to yoke end

→ Eddy current are predominant at magnet ends (Strong amplitude due to end plates)

→ Tendency to higher relative amplitude of Eddy currents effects in short magnets

MTE octupole



Conclusion

→ Theoretical expectations based on simple models are verified on individual magnets (e.g. amplitude proportional to dB/dt)

→ Our data collection cannot be used to make statistical predictions.
Some vital parameter such as the inter-lamination resistivity appears to be missing

→ Accurate circuital or FE modeling of eddy current effects is impractical due to high computational load and many poorly known parameters

→ Measurements are essential to validate magnet design. The simple method used gives good results and covers time scales from a few μs to 1 seconds

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