Rapid Scan Workshop

University of Denver
July 28, 2013

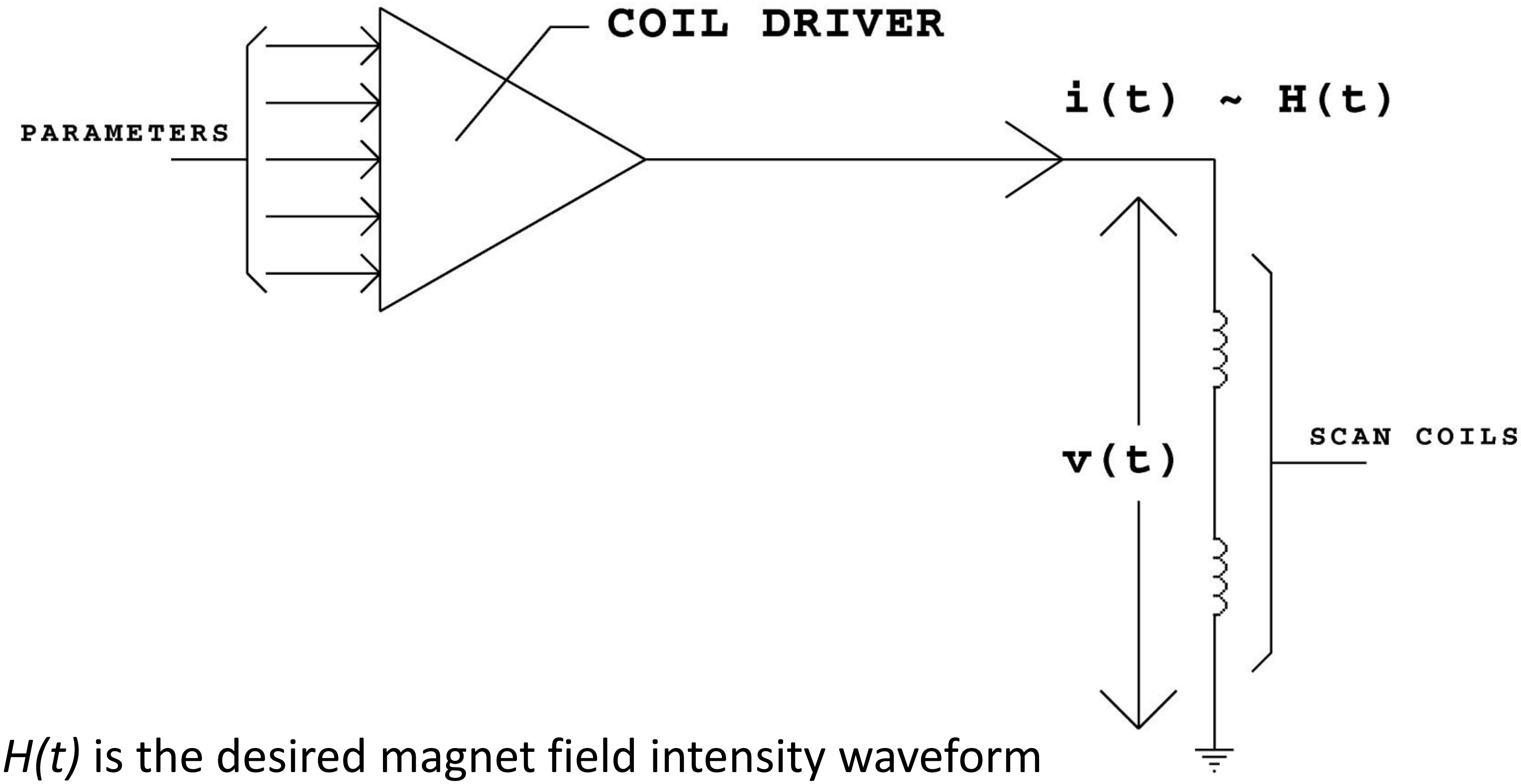
Scan Coil Drivers

Richard Quine

Outline:

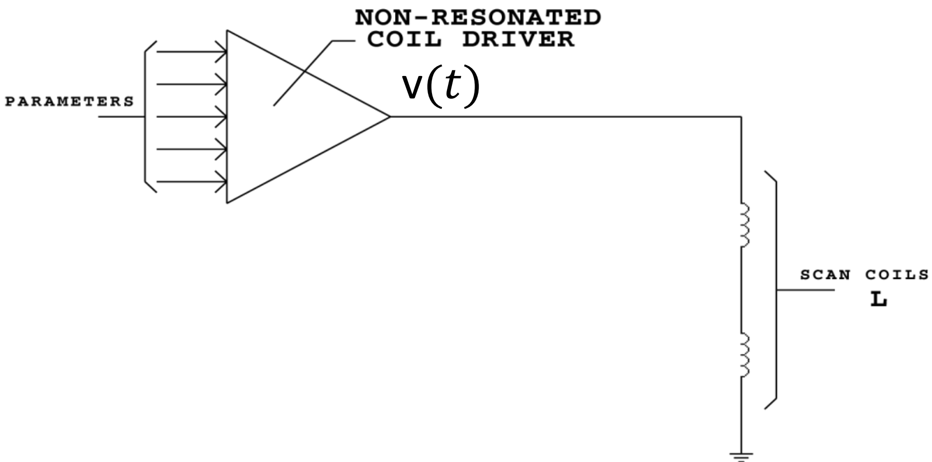
- What is a scan coil driver?
- Types of coil drivers : Non-resonated, resonated
- Design challenges for coil drivers
- Scaling laws
- Coil driver design: Non-resonated
- Coil driver design: Resonated
- Coil driver usage limitations: System bandwidth

Basic coil driver



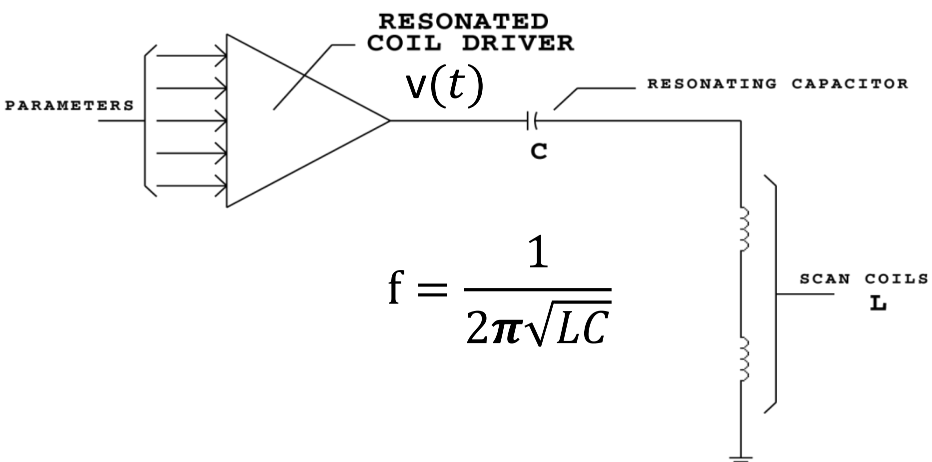
- *H(t)* is the desired magnet field intensity waveform
- *B(t) = μH(t)* is the desired magnetic flux density waveform
- To first order approximation, *B(t)* is linearly proportional to current, *i(t)*
- For a practical design, the coil driver can produce only a controlled *v(t)*
- *V(t)* must be such that the desired *i(t)* is obtained

Non-resonated and resonated coil drivers



$$v(t) = L\frac{di}{dt} + iR$$

ARBITRARY CURRENT WAVEFORM, COMMONLY TRIANGULAR

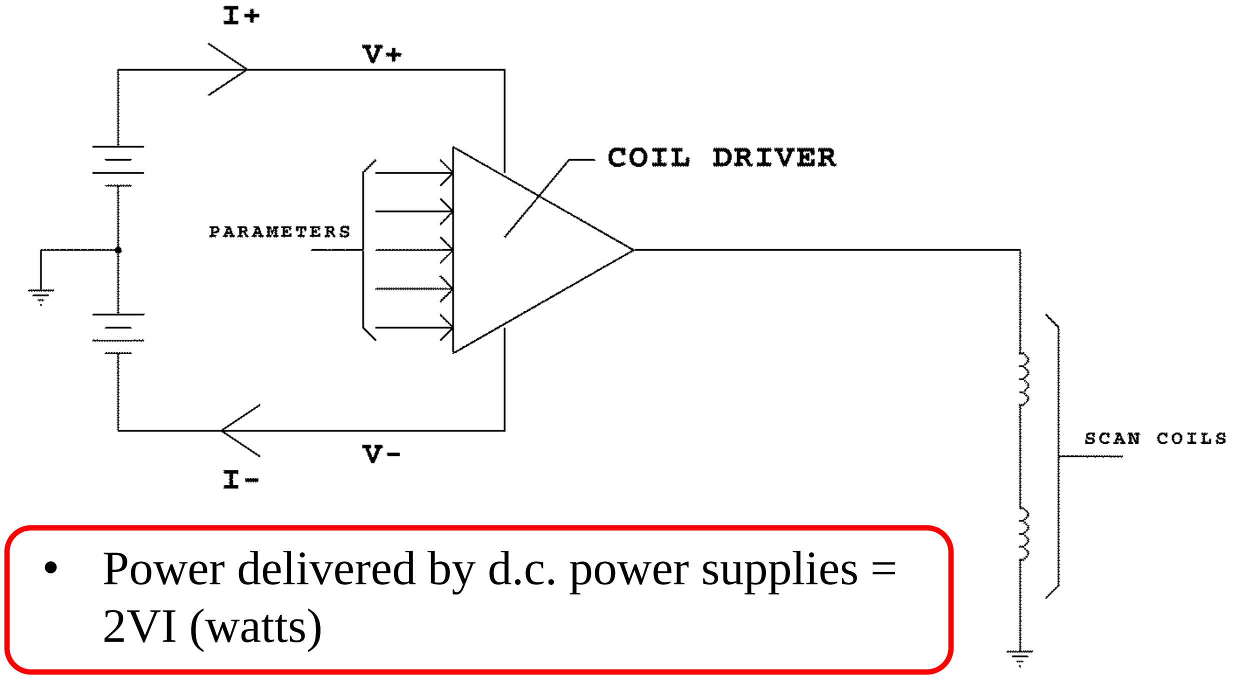


$$f = \frac{1}{2\pi\sqrt{LC}}$$

$$v(t) = iR$$

SINUSOIDAL CURRENT WAVEFORM

Challenges to coil driver design: Coil drivers need power supplies

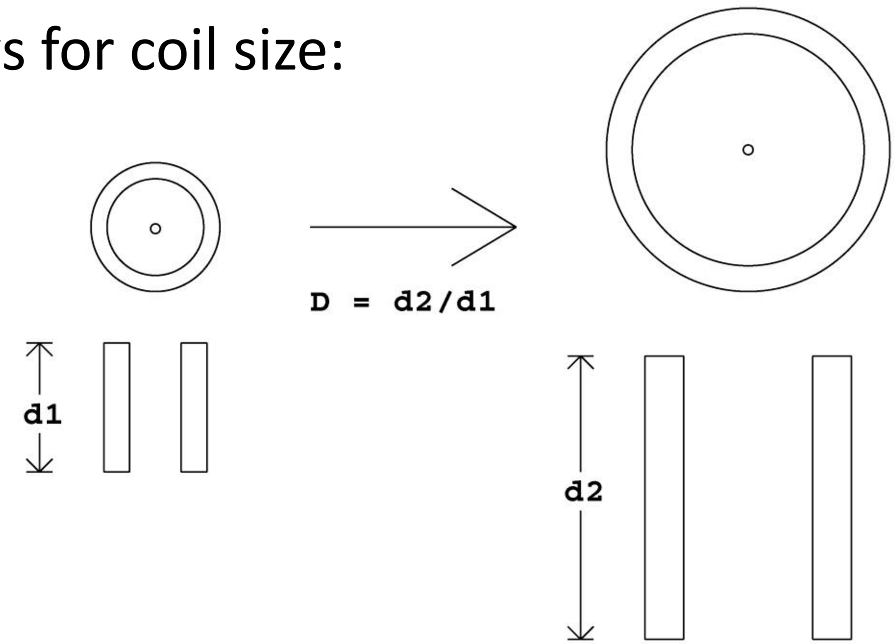


- Power delivered by d.c. power supplies = 2VI (watts)

- Cost and Complexity of the coil driver is roughly proportional to the power handled by the coil driver

How is coil driver power affected by coil size?

Scaling laws for coil size:



Larger coils are needed for:

1. Larger resonators for lower microwave frequencies
2. Imaging
3. More homogeneous scan fields

Coil driver power is greatly affected by coil size

$D = \frac{d_2}{d_1}$; $PWR(D)$ is coil driver power as function of D;

$$\mathrm{v}(t) = L\frac{di}{dt} + iR \qquad Coil\ Constant \propto \frac{1}{D}$$

- Non-resonated driver, constant current, variable # of turns:
  $$PWR(D) \propto D^4 + D^2$$
- Non-resonated driver, constant turns, variable current:
  $$PWR(D) \propto D^4 + D^3$$
- Resonated driver, constant current, variable # of turns:
  $$PWR(D) \propto D^2$$
- Resonated driver, constant turns, variable current:
  $$PWR(D) \propto D^3$$

Coil size scaling examples

Scaling up classic CW modulation coils to mouse imaging size

Non-resonated, constant turns:

$PWR\ (D) \propto \left(\frac{90}{25}\right)^4 + \left(\frac{90}{25}\right)^3$ is a factor of 214

Resonated, constant turns:

$PWR(D) \propto \left(\frac{90}{25}\right)^3$ is a factor of 46

Other scaling laws

- Scan frequency scaling: $F = \frac{f_2}{f_1}$

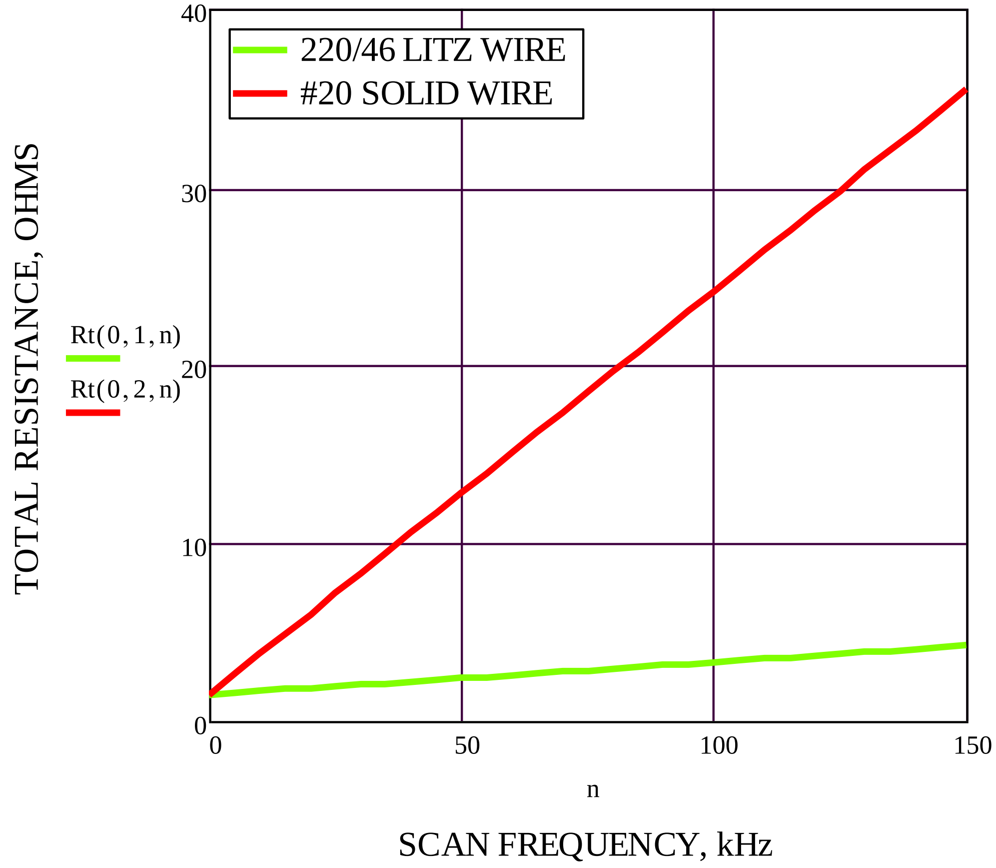
Non-resonated:

$PWR(F) \propto F$ (ignoring resistive term)

Resonated:

$PWR(F) \propto R(F)$, $R(F) = R_{dc} + R_{ac}(F)$

Total resistance of wire for 60 turns, 76 mm diameter coils, Litz and solid wire



- Scan width scaling: $W = \frac{w_2}{w_1}$

Non- resonated:

$$PWR(W) \propto W^2$$

Resonated:

$$PWR(W) \propto W^2$$

COIL DRIVER DESIGN: NON-RESONATED

Driver must produce a voltage across the coils of the form

$$\text{v}(t) = L\frac{di}{dt} + iR$$

Where the only reasonably constant term is *L*.

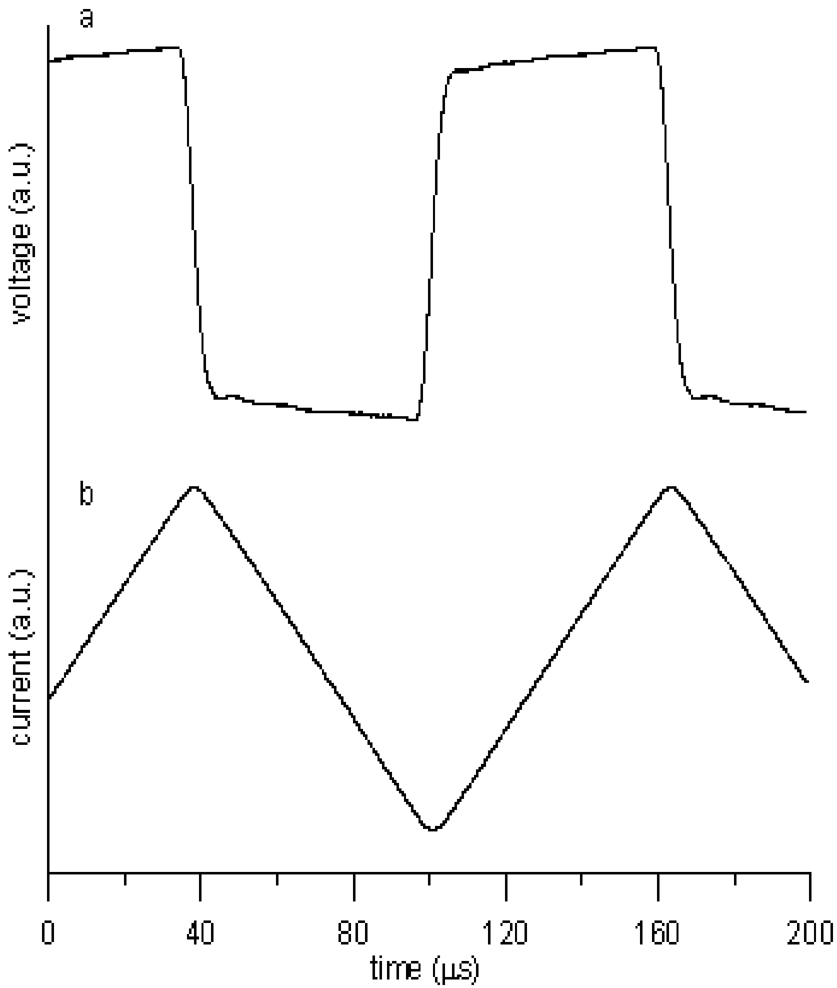
The derivative term is a function of both scan width and scan frequency.

The coil resistance, *R*, is a function of coil temperature and scan frequency.

Typical voltage and current for a triangular scan

$$\mathrm{v}(t) = L\frac{di}{dt} + iR$$

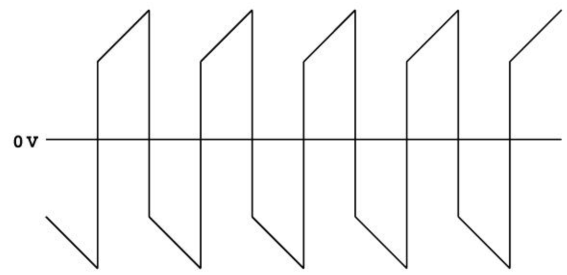
$$i(t)$$



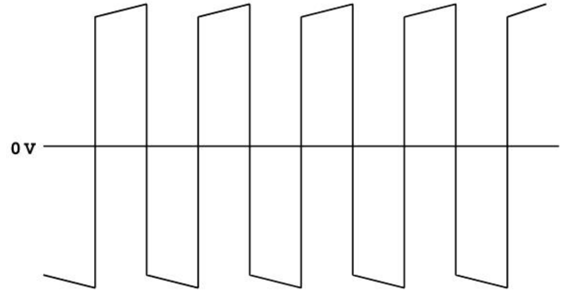
V(t) shape is highly variable.

Idealized examples for triangular field scans:

- *v(t)* for low frequency, high sweep width:



- *v(t)* for high frequency, low sweep width:



Solution for producing *v(t)*

- Needed: a circuit to compute *v(t)* in real time within the operational limits of scan width, scan frequency, coil inductance and coil resistance.

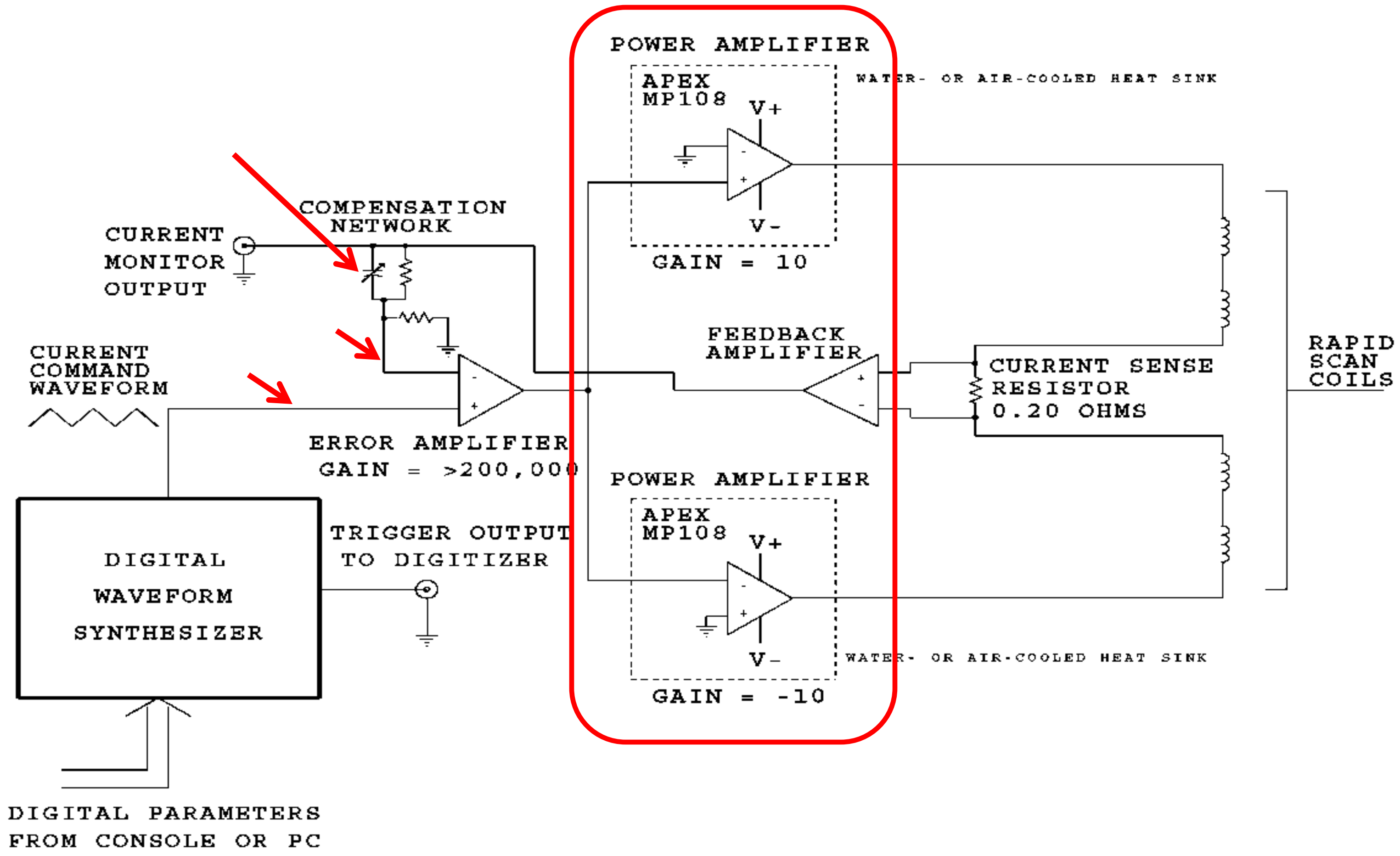
- Solution: a high-gain feedback circuit in which desired current wave shape is compared to actual current wave shape to find the error, *E(t)*. The error is then multiplied by a large gain to produce *v(t)*.

- $v(t) = E(t) * 4 * 10^6$

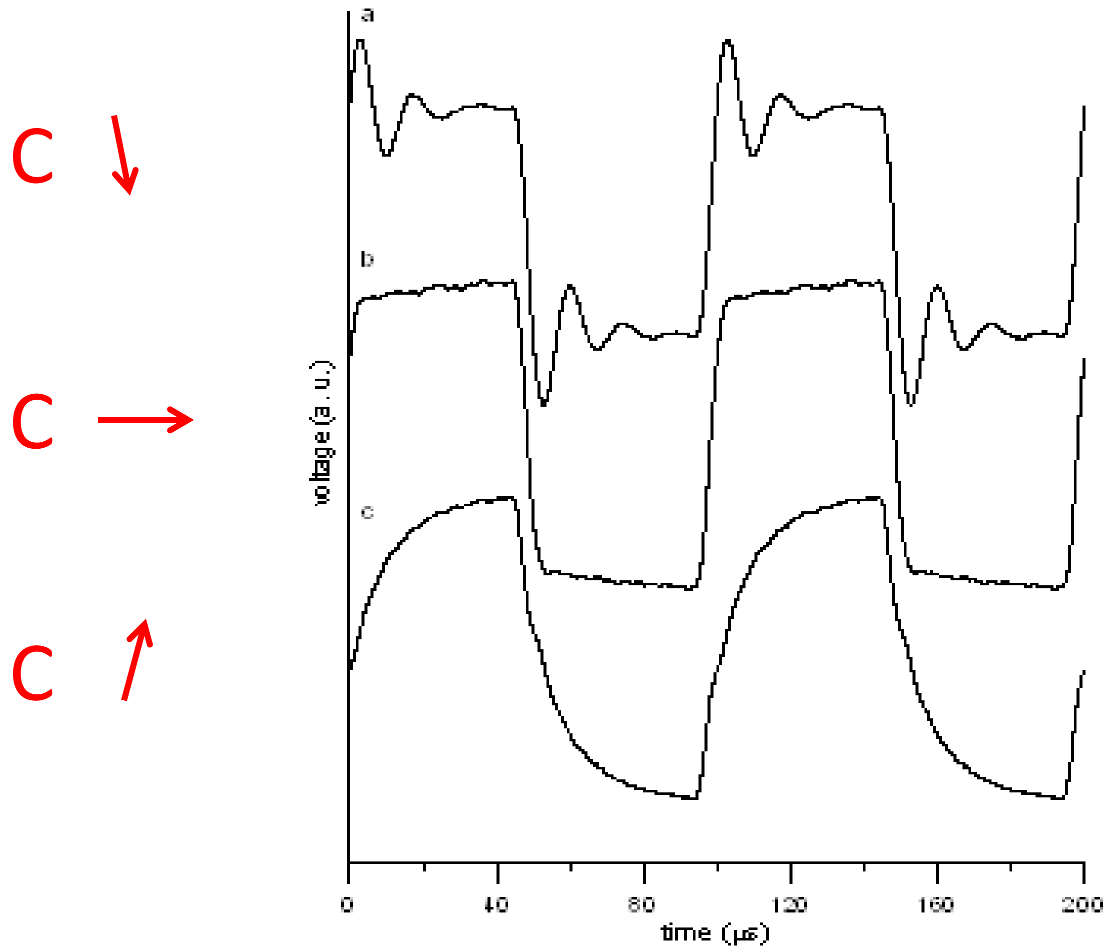
- $E(t) = \frac{v(t)}{4*10^6}$

- For *v(t)* of a few tens of volts the error is very small.

Non-resonated driver block diagram



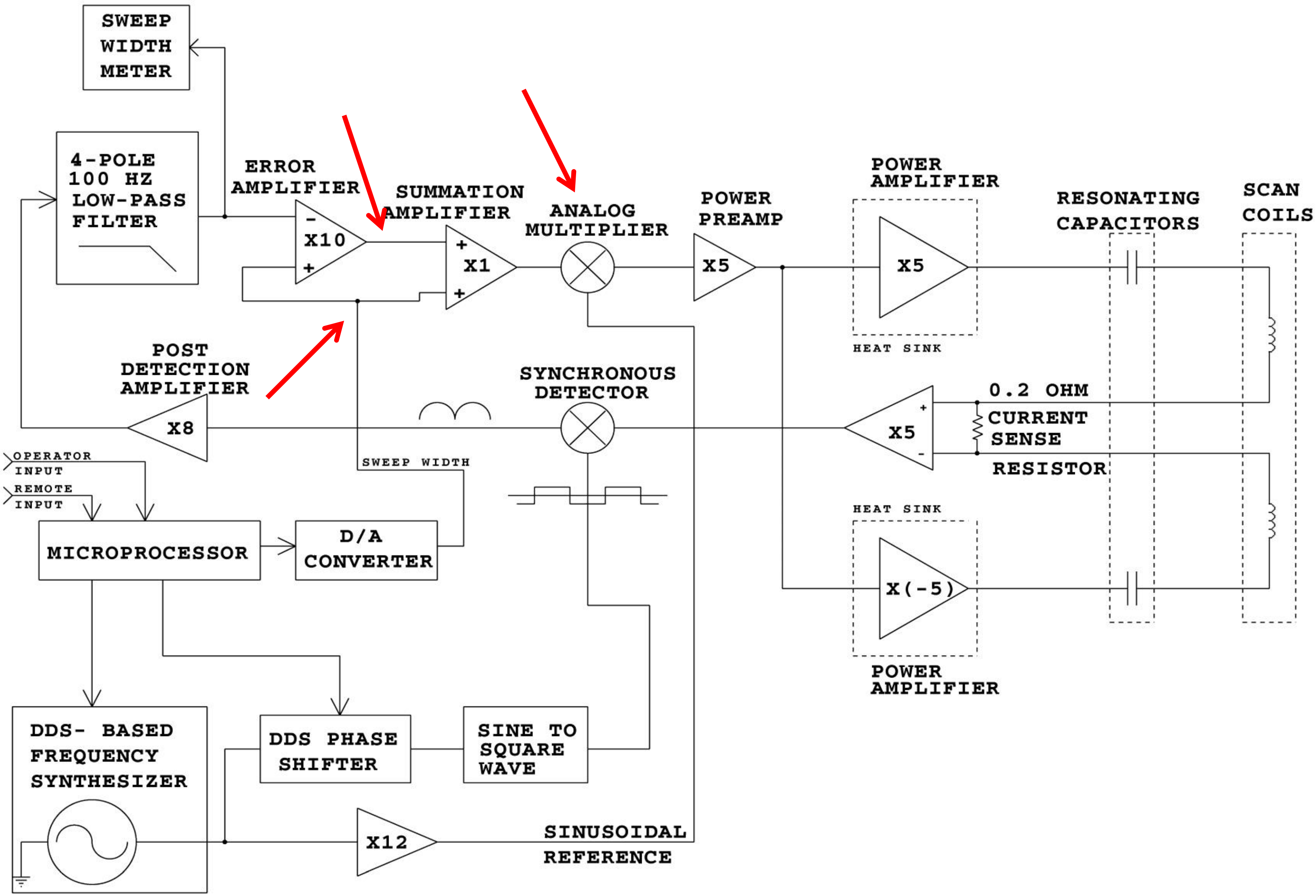
High gain loop needs compensation for stability and high linearity



Resonated coil driver is much simpler

- No need to compute v(t) wave shape- always sinusoidal
- Feedback only needed to stabilize scan width amplitude
- Cooling requirements are much less
- Less sensitivity to coil dimensions

Resonated coil driver



Coil driver usage limits: System bandwidth

- Maximum scan rate is limited by resonator bandwidth. The bandwidth *available* for a rapid scan signal is:

$$BWA(Q) = \frac{f_0}{2Q_L}$$

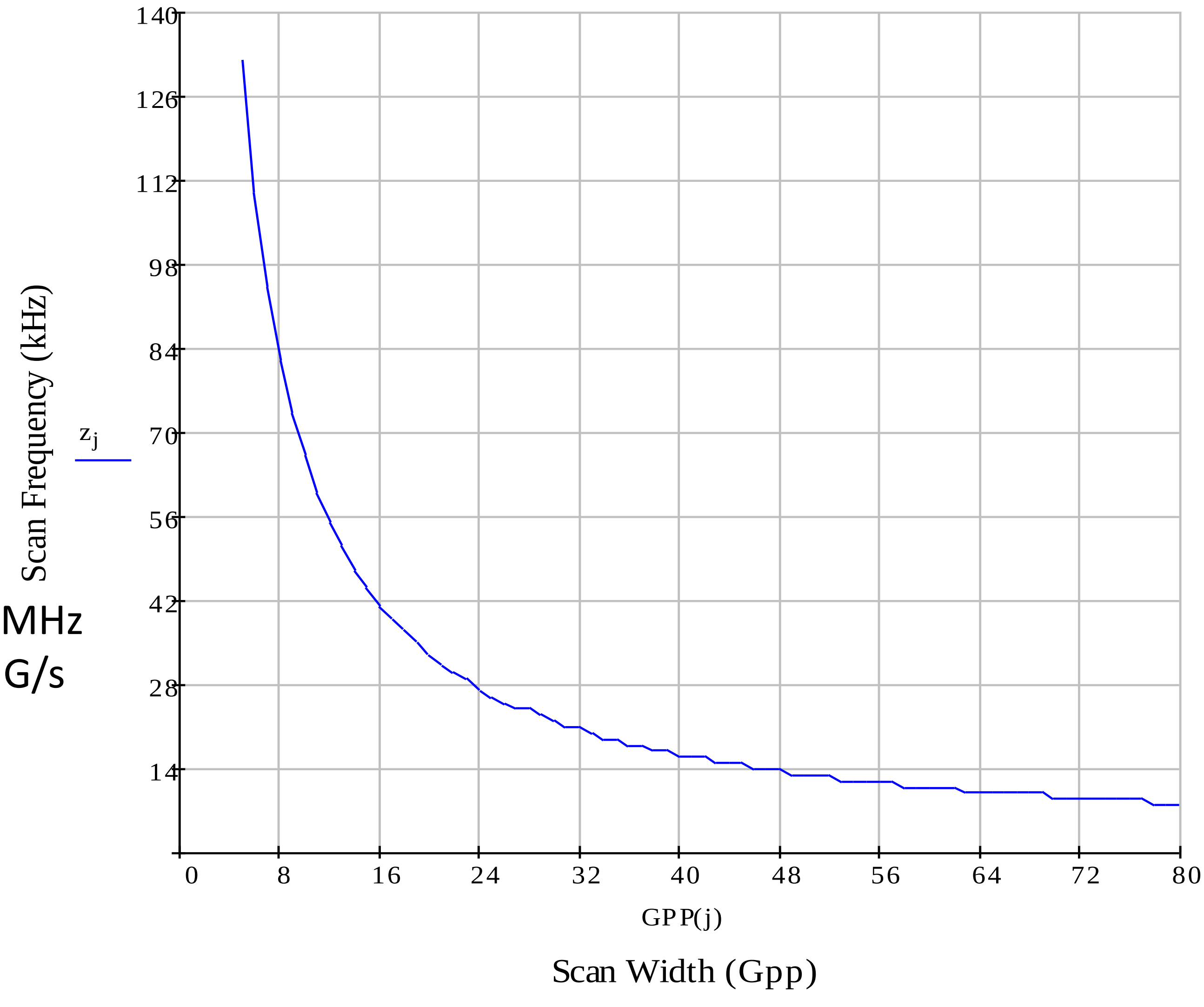
½ of full resonator BW for up scan and ½ of full BW for down scan.

- Bandwidth *required* is proportional to scan rate and relaxation time (or inversely to line width).
- $BWR(a, T_2) = \frac{a\gamma N T_2}{2\pi}$

N = number of relaxation times to include, usually between 4 and 8 depending on resolution desired.

Constant rate curve

fo = 250 MHz
Q = 30
CWLW = 0.5 G,
Gaussian line, N = 5
Available Bandwidth = 4.2 MHz
Maximum Scan Rate = 2 MG/s



Summary

- Coil driver requirements increase non-linearly with coil size.
- Resonated and non-resonated drivers are substantially different designs.
- Application of high performance coil drivers is usually constrained by bandwidth limitations.

Acknowledgements

The Eaton Group principals:

Dr. Gareth Eaton

Dr. Sandra Eaton

Dr. George Rinard

Dr. Mark Tseytlin

Our wonderful group of **graduate students** who use coil drivers:

Josh Biller

Hanan Elajaili

Deborah Mitchell

Zhelin (Jason) Yu

Bruker Biospin for their sponsorship of this workshop