Quench Studies of a Prototype Superconducting Undulator

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Outline

- Goals of the studies
- Description of the prototype undulator assembly
- Details of a technique for measuring inductance of each coil during slow ramps
- VI Waveform analysis during quenches and power supply shutdown
- Details of technique for determining the dynamic impedance of each coil during a quench event
- Calculation of copper and eddy current core losses, power and energy
- Description of Agilent power supply and it’s down programming operation
- Conclusions

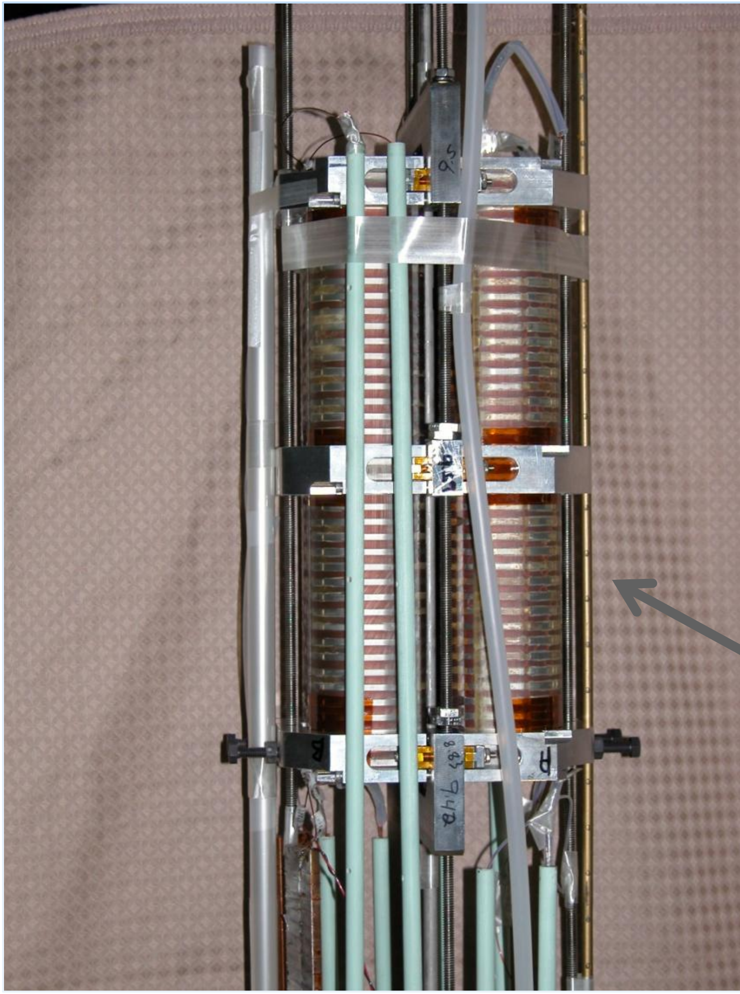
Goals of the studies

- Understand the dynamics of the SCU and power supply system during a quench
- Determine if a quench protection circuit is required in addition to that already provided by the power supply
- Characterize the dynamic impedance of the SCU and try to determine the Energy transfer during a quench

The prototype AL core superconducting undulator

- Two cores each consisting of 42 steel poles and 41 coils continuously wound on an aluminum core.
- 16 mm period 9.5 mm gap
- Supercon 0.74 mm NbTi conductor with Formvar insulation 39 turns per coil except the last two coils on each end
- Design current 500 A, typical quench current of about 820 A
- Testing done in a vertical cryostat with LHe bath
- Heaters installed on each core to provide on demand quench of either coil
- Voltage taps installed at Cu/SC joints for measurement of the SC impedances

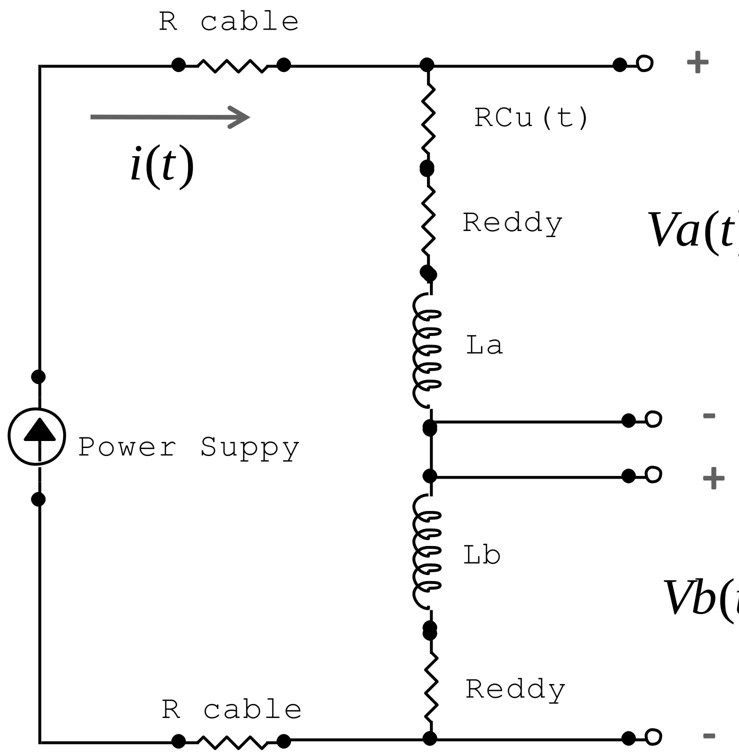
42 Steel Poles with Aluminum Core NiTi SCU



Measurement Techniques

- Voltage taps were installed at the Cu/SC solder joints for each coil
- Power supply current measured with Danfysik current transducer
- VI waveforms captured with a DSO and a 24 bit Digital Signal Analyzer module
- Polarities are such that a positive coil voltage indicates an IR drop and a negative voltage is due to the negative Ldi/dt due to the negative current decay rate

Simplified 1st order LR circuit

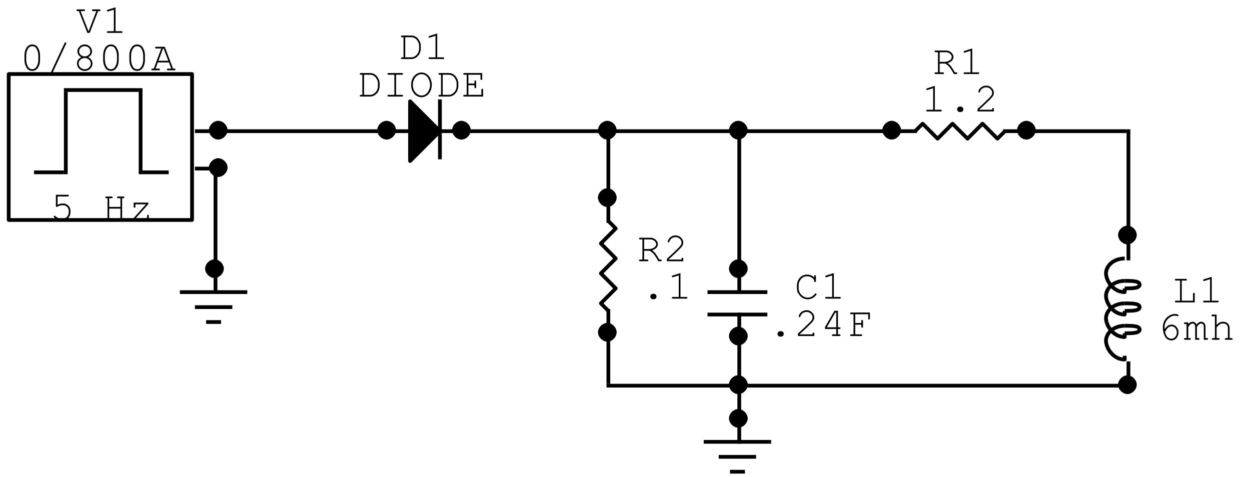


$$Va(t) = i(t)Rb(t) + \frac{di(t)}{dt}L(t)$$

Voltage taps

$$Vb(t) = i(t)Rb(t) + \frac{di(t)}{dt}L(t)$$

Simplified 2nd order circuit model including power supply



Spice modeling shows:

If R2 < R1/10; the current time constant will approximately = L1/R1

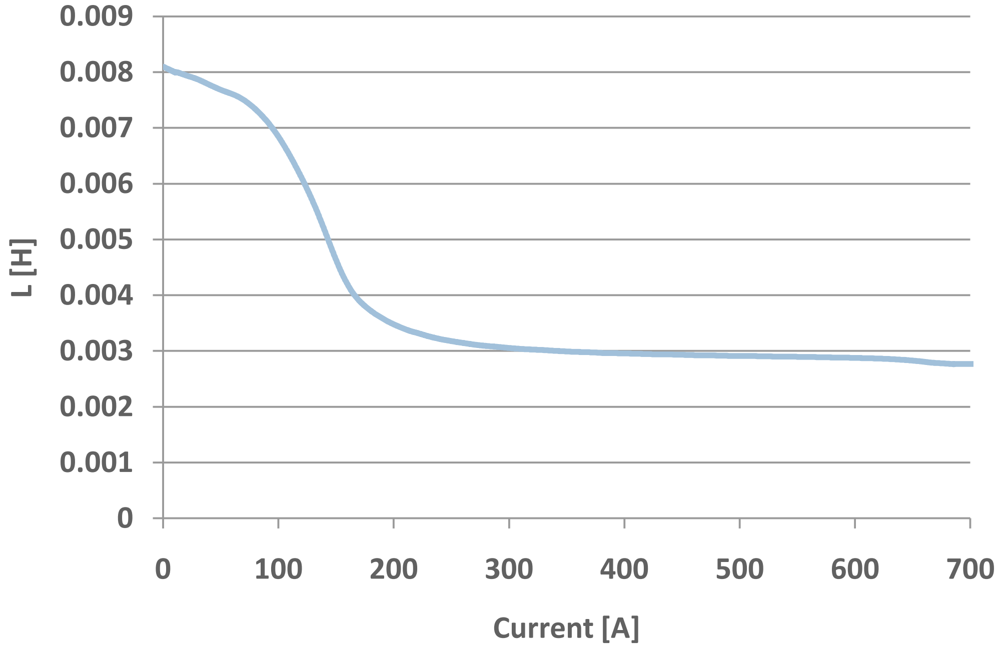
So a simple 1st order LR series circuit can be used to estimate R1

Measurement of the inductance of the SC coils from 10 to 700 Amperes

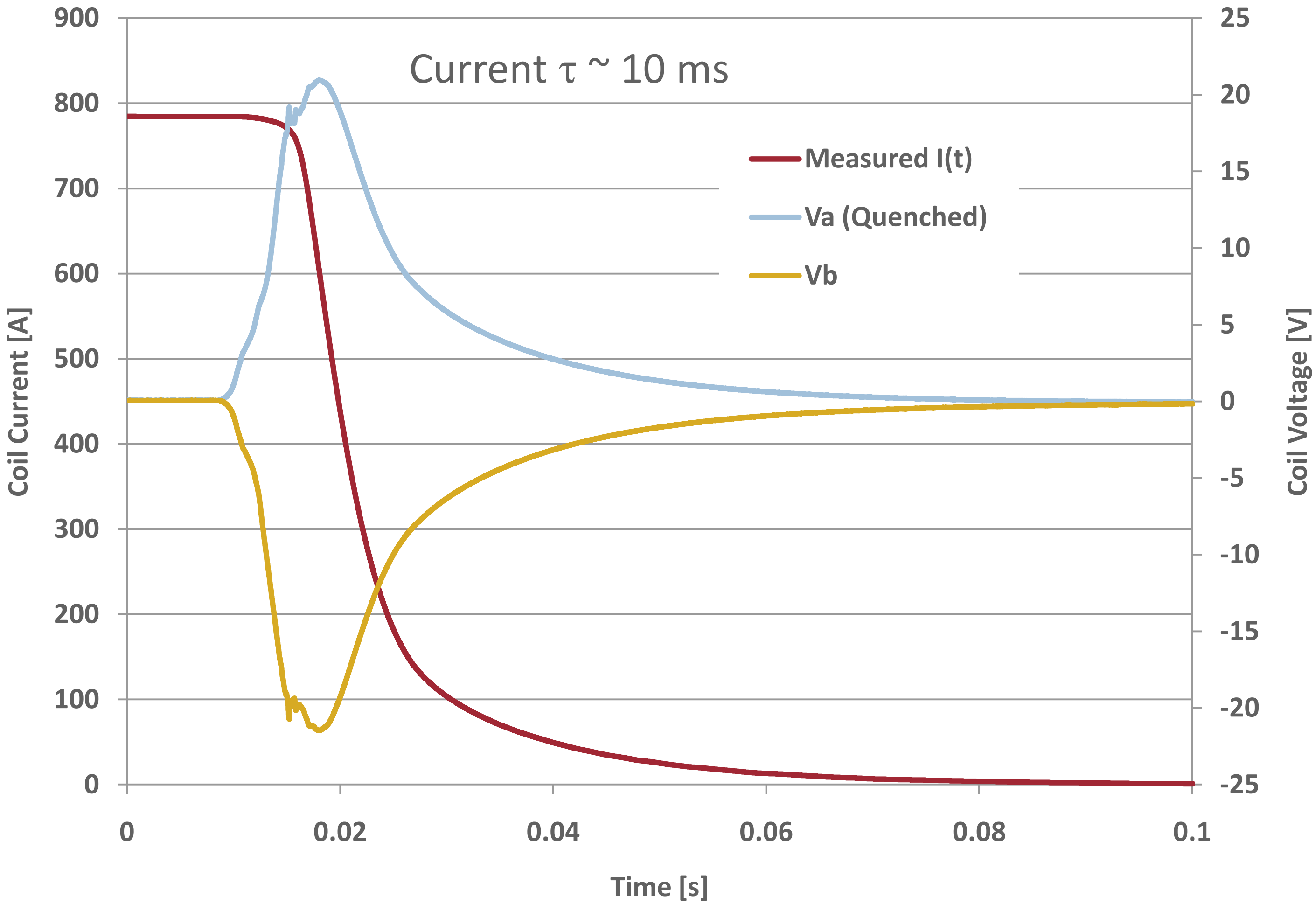
- The current was ramped up and down at constant rates of 1, 5, and 10 A/s while sampling the coil voltages and current.
- The ramp rate was slow enough that the eddy currents are insignificant. The difference of L due to the steel hysteresis is quite small and we chose to use the curve with a negative di/dt which will be the case during a quench
- The inductance was calculated by dividing the coil voltage by the ramp rate at each sample.

Typical measured inductance of one coil as a function of current

$$L(t) = \frac{V(t)}{\frac{di}{dt}(t)}$$



VI coil waveforms; natural quench event at 785A Positive voltage indicates the IR magnitude is positive and is thus the quenched coil



How can the copper losses for the quenched coil be determined?

- The inductance measurements of each coil show they are almost identical. Using this assumption, the instantaneous impedance $Z(t)$ of each coil can be easily calculated by dividing the instantaneous voltage $V(t)$ and currents $i(t)$.
- It has been shown that during a typical quench only one coil becomes normal.
- Assuming the eddy current resistance and inductive reactance of each coil is the same due to common $i(t)$ and $di(t)/dt$, the quenched coil has an added impedance $Rcu(t)$ due to the Cu resistance. Taking the difference of the two coil impedances will yield the $Rcu(t)$. In the case of the waveforms of the previous slide coil “a” quenched and thus has a positive impedance.

$$Za(t) = \frac{Va(t)}{i(t)} = R_{Cu} + R_{Eddy} + \frac{1}{i(t)} La(t) \frac{di}{dt}(t)$$

$$Zb(t) = \frac{Vb(t)}{i(t)} = R_{Eddy} + \frac{1}{i(t)} Lb(t) \frac{di}{dt}(t)$$

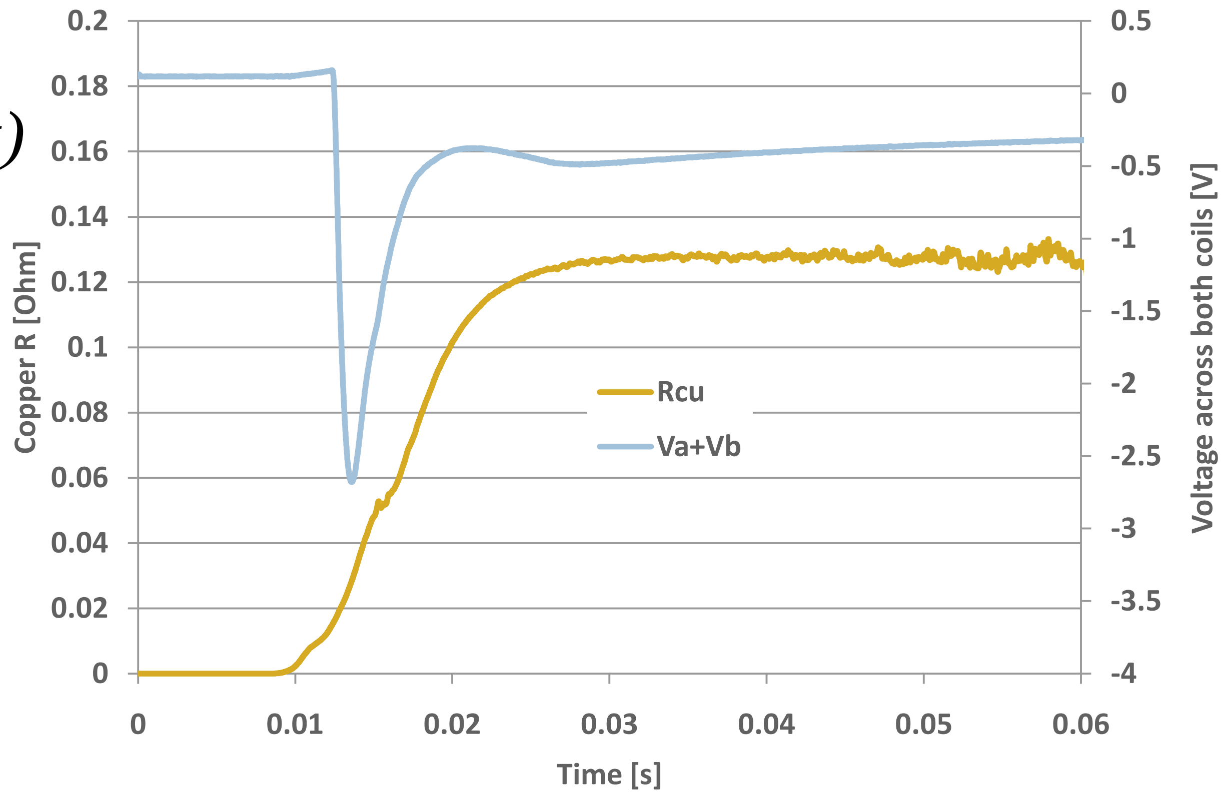
$$R_{Cu}(t) = Za(t) - Zb(t)$$

Calculated Copper resistance and the Voltage across both coils showing when the PS shuts off

Time for PS to shut off from onset of quench ~ 5ms

Rcu peaks at ~ 130 mΩ

$$R_{Cu}(t) = Za(t)\text{-}Zb(t)$$



Steps to determine $Z(t)$ of each coil when only one coil quenches and the $La(t) = Lb(t)$

- Measure the $La(i)$ and $Lb(i)$ at slow ramp rates i.e 1, 5, 10 A/s
- Use the measured $L(i)$ as a lookup table when analyzing the VI waveforms during a quench event.
- $Za(t) = \frac{Va(t)}{i(t)}$ $Zb(t) = \frac{Vb(t)}{i(t)}$ Impedance of Coil a and b respectively
- $R_{Cu}(t) = Za(t)-Zb(t)$ Cu resistance of quenched coil "a" since $Za(t)$ is positive
- $R_a(t) = \frac{Va(t) - L(t)\frac{di}{dt}(t)}{i(t)}$ Total Resistance of quenched coil "a"
- $R_b(t) = \frac{Vb(t) - L(t)\frac{di}{dt}(t)}{i(t)}$ Total Resistance of coil "b" (due to eddy currents only?)
- The resistive component of Coil "b" is likely only equal to the eddy current resistance since this coil doesn't quench

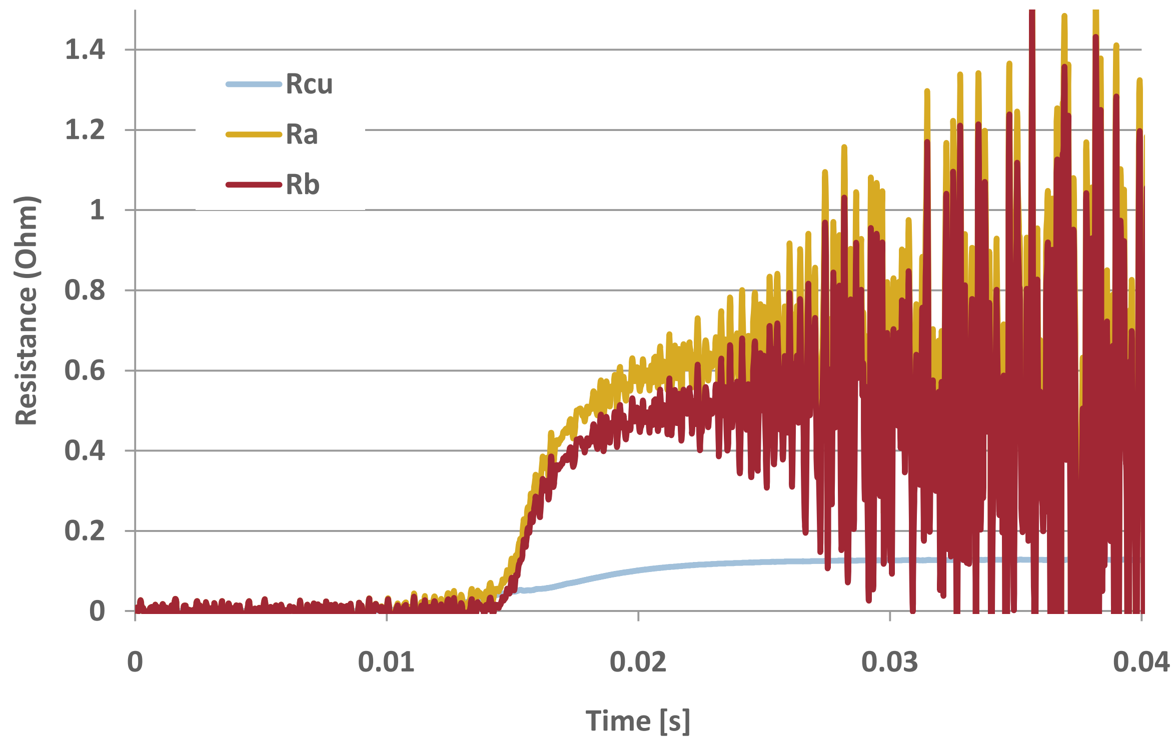
Resistance of Both "a" and "b" coils during quench

Data becomes noisy due to limited resolution of current and numerical calculation of di/dt as current approaches zero

$$R_{Cu}(t) = Za(t) - Zb(t)$$

$$R_a(t) = \frac{Va(t) - L(t)\frac{di}{dt}(t)}{i(t)}$$

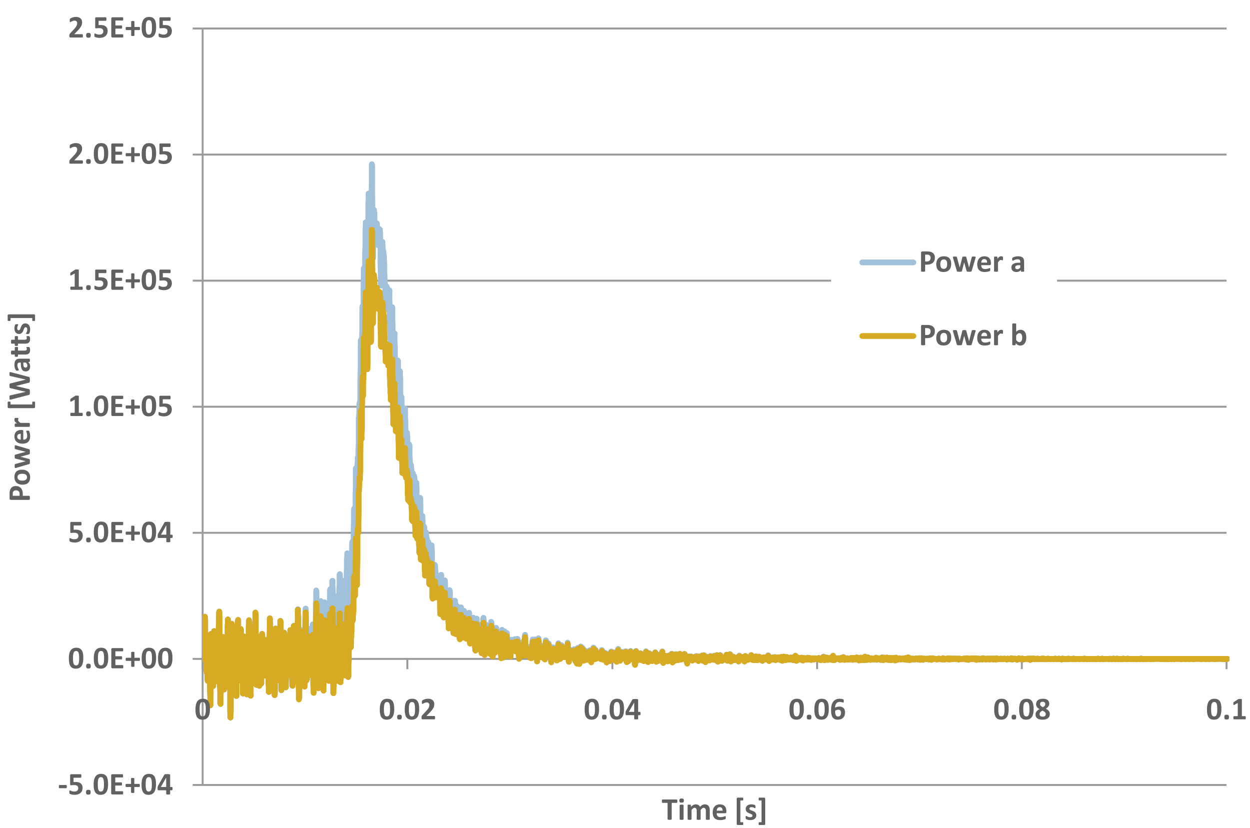
$$R_b(t) = \frac{Vb(t) - L(t)\frac{di}{dt}(t)}{i(t)}$$



Calculating Power and Energy transfer for each coil

- The power is calculated using the copper R_{Cu} and eddy current R_{Eddy} resistances for each coil:
- $$Pa(t) = I^2(t)\left[Ra(t) + Ra_{Eddy}(t)\right] \qquad Pb(t) = I^2(t)Rb_{Eddy}(t)$$
- $$Ea(t) = \int_0^T Pa(t)dt \qquad Eb(t) = \int_0^T Pb(t)dt$$
- $Eo = \frac{1}{2} I_o^2 L_o$ This is the energy stored in each coil at the initial current and inductance Io = 785A and Lo = 2.76 mH per coil. Total initial energy per coil is 850 J

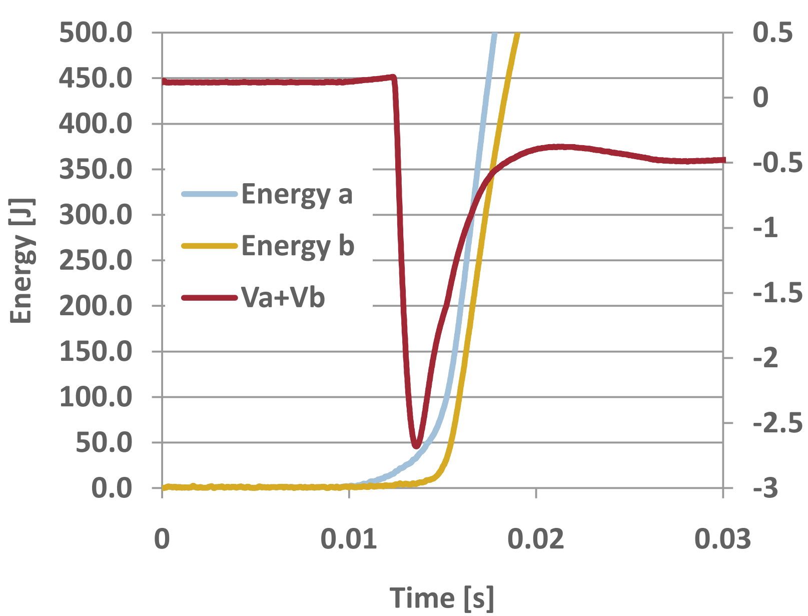
Instantaneous power dissipation of coils “a” and “b”

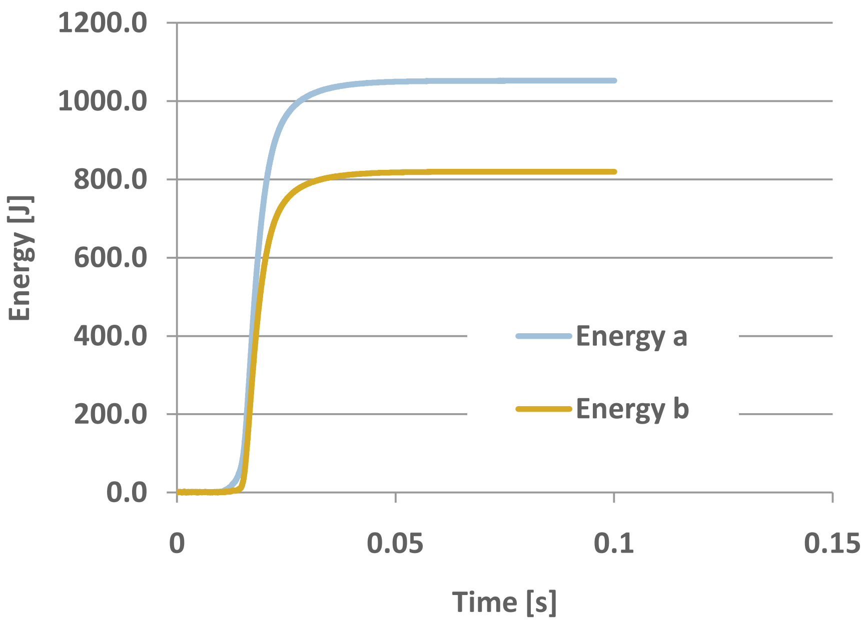


Calculated Energy transfer from coils to core and copper

Total calculated Energy transfer ~ 1870 J
88% apparently absorbed by AL core
The remaining going to Cu
These are rough numbers but seem to be reasonable

Eo per coil = 850 J
Final Ea = 1052 J
Final Eb = 820 J
Energy into Cu = 232 J

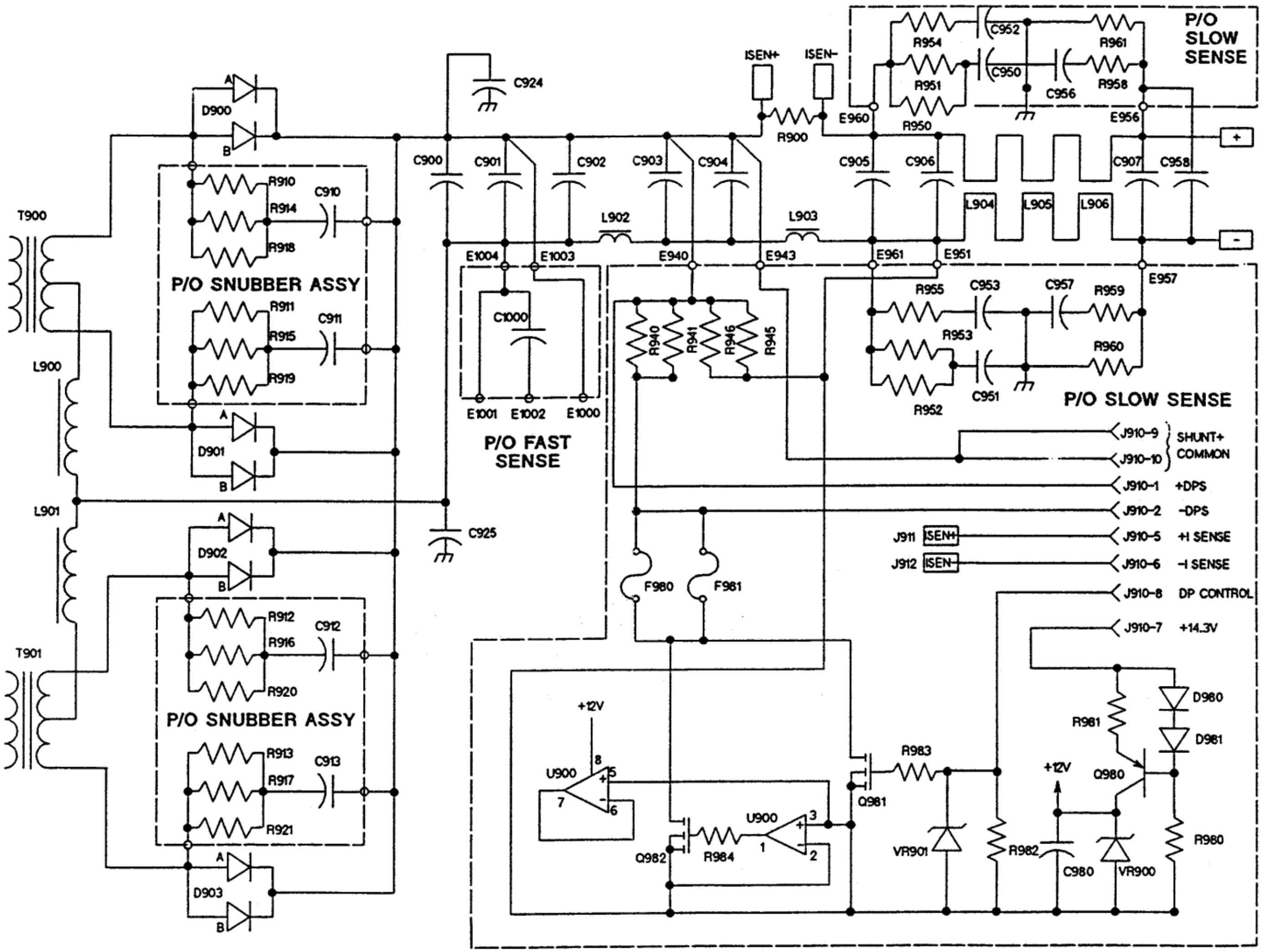




Agilent 6680A Power Supply

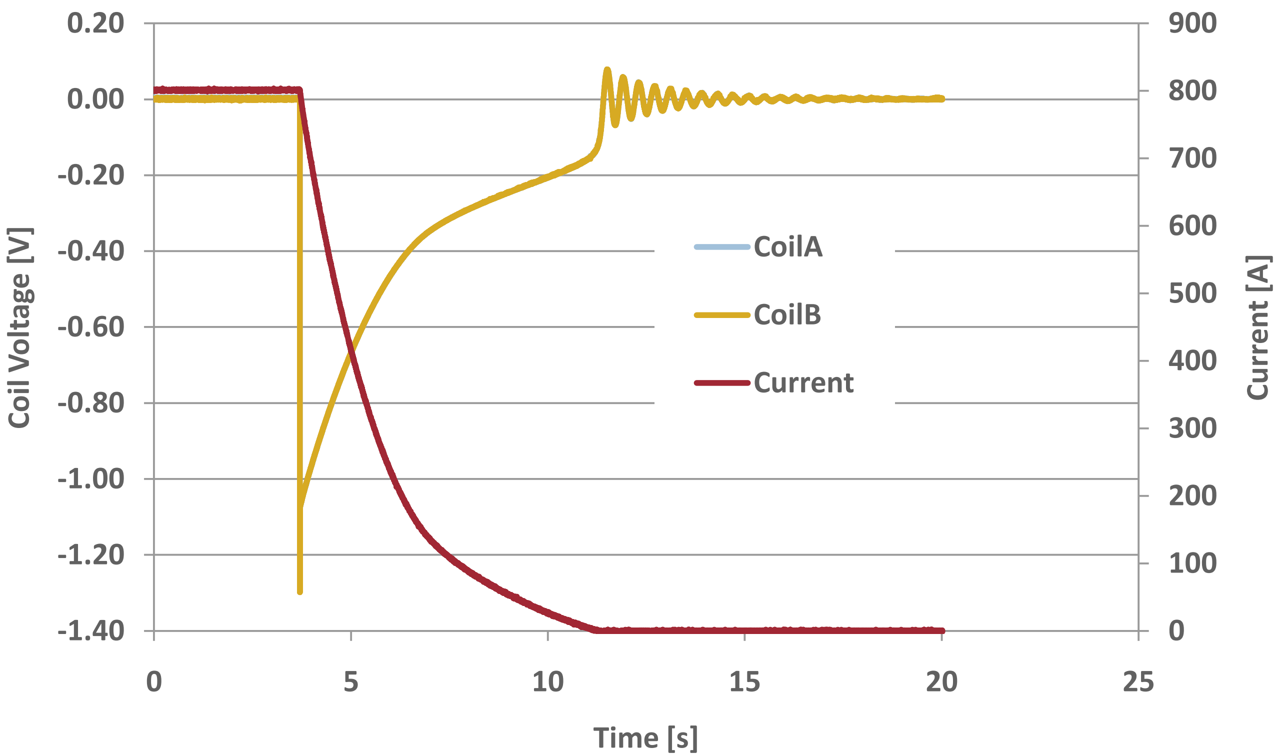
- An Agilent 6680A PS has been used for several years for all the prototype SCUs at the APS.
- Vmax = 5V, Imax = 875A This supply has a programmable Over Voltage Protect, OVP feature which is ideal for shutting down the supply during a magnet quench.
- Typically the OVP is set to about 0.5V above the nominal voltage at maximum current. The PS terminal voltage rises shortly after the onset of a quench and upon reaching the set-point, the PS shuts off the current supply and introduces a dynamic shunt resistance to reduce the current as fast as possible. This is Agilent's "down programming" feature.
- This shunt resistance is very low in the 10s of mΩ so dissipates very little power, but allows the current decay to be mostly dependent on the L/R of the load.
- In addition to the down programming feature the rectifiers off the secondary of the PWM transformers provide a "Flyback" feature which prevents the terminal voltage from exceeding about -2 volts. This protects the filter capacitors from high reverse voltage, but has the added benefit of absorbing some of the stored energy of the coils during an AC power shutdown when the down programming circuit would not be functional.

Agilent 6680A output stage schematic



Response of the SCU During an AC input shutdown

- To study the effect of an AC power shutdown, the coils were energized to 800A then the AC power feed was disconnected
- Amazingly the SCU coils did not quench. The current decay time constant was very long. The following plot shows the IV waveforms:



Summary

- The losses due to the normal Cu and eddy currents were calculated by knowing the inductance of the coils as a function of current, and having the VI waveforms.
- Knowing the dynamic resistances and currents for each coil, the instantaneous power and energy was calculated.
- If the method to determine the Cu and core losses is correct, about 88% of the stored energy in the coils is transferred to the core as eddy currents.
- The Agilent 6680A power supply OVP feature shuts down the PS (when set to 0.5 V above nominal) in approximately 5 ms from the onset of the quench. The added energy from the PS transferred to the Cu conductor is about 30 to 40 Joules
- From the results of these measurements it seems reasonable to conclude that additional quench protection circuits are not required for a magnet of this small inductance and relatively low core resistivity.
- Ongoing measurements are being done to improve the accuracy of these measurements and exploring other methods of analysis
- Measurements of the coil impedances are also being done by modulating the power supply with AC at fixed DC levels to determine the frequency dependence of the L and R.