Power-Supply System Architecture, Controls, and Protection for EIC Hadron Storage Ring Superconducting Magnets

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Electron Ion Collider

IEEE Long Island (LI) Power Electronics Symposium

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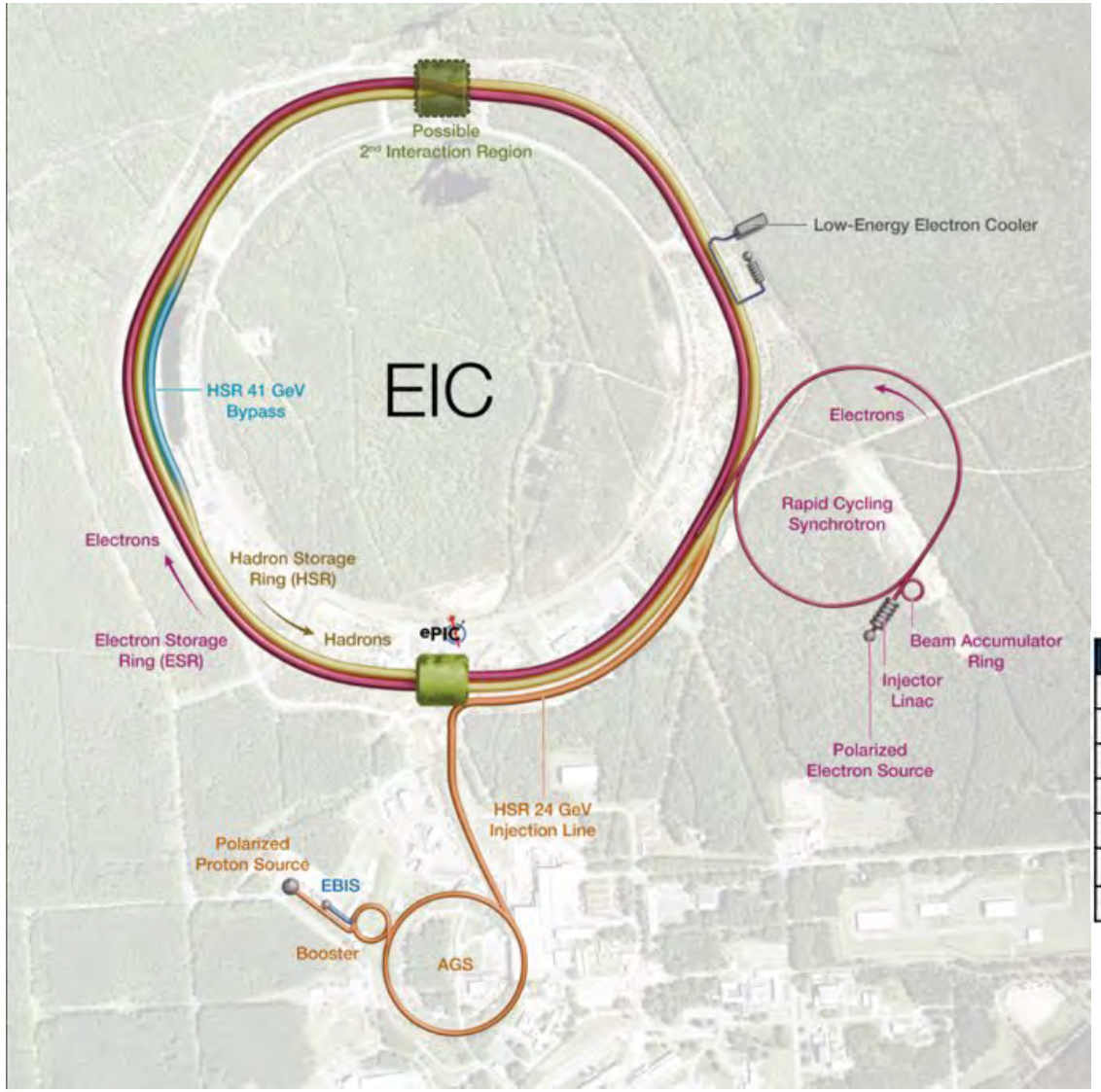
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Outline

1. Electron Ion Collider – Hadron Storage Ring
2. Power Supplies for Superconducting Magnets
   - Precision Current-Regulated Power Supply
3. Quench Protection of Superconducting Magnets
   - Hot Spot Vs Peak Voltage
   - Quench Detection
4. HSR Power Supply System
   - Main Magnet Power Supplies
   - Ground Fault Analysis
5. Summary

Electron Ion Collider



- Polarized Electron Gun- 350kV
- S-Band Linac – 50 -750MeV
- Rapid Cyclic Synchrotron
  - 750MeV – 9/18 [GeV]
  - Circumference : 1500[m]
- ESR – Electron Storage Ring
  - 5 – 18[GeV]
  - Circumference : 3833.845[m]

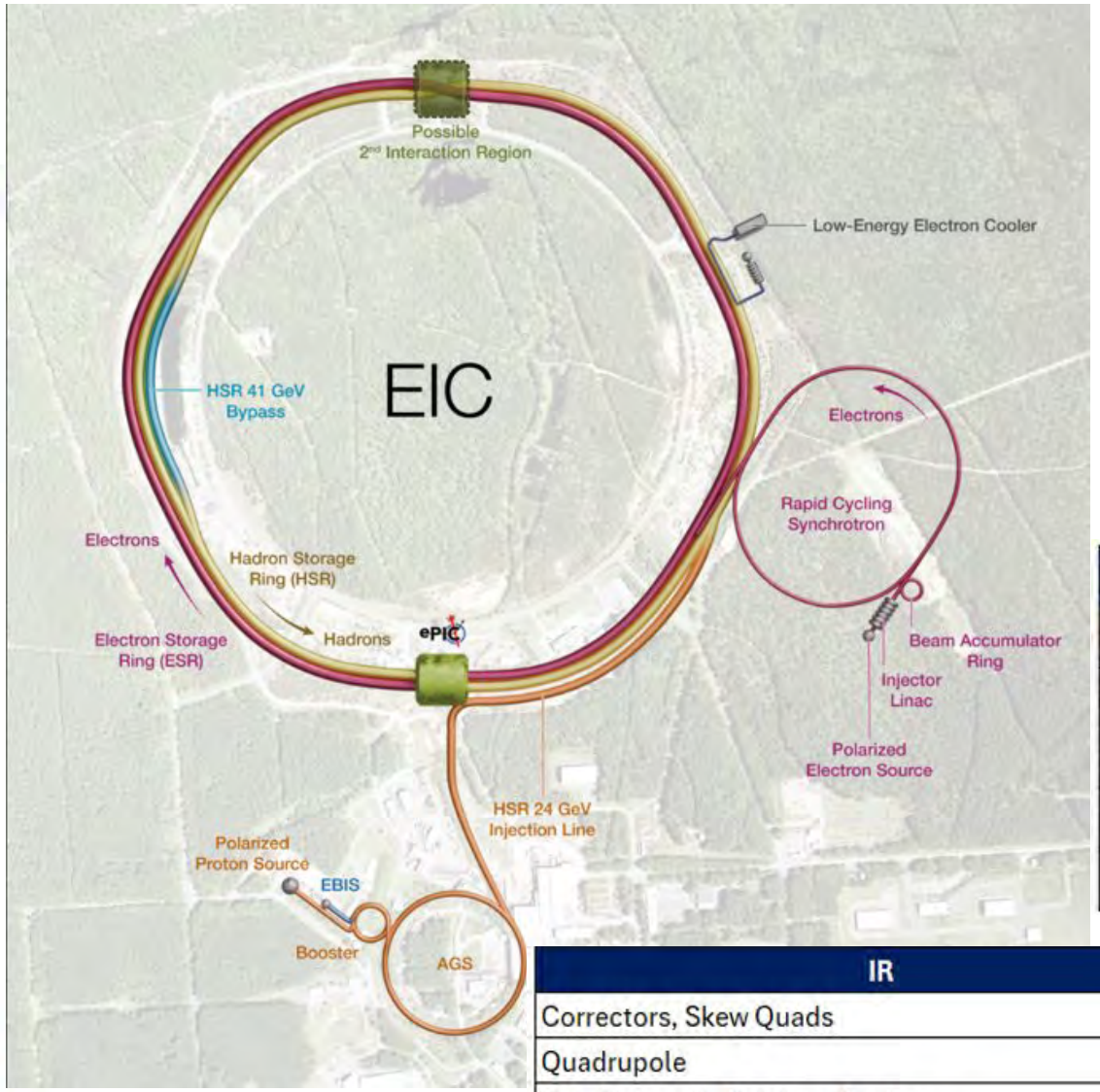
Magnet Type	Number of Powered Circuits	Number of Power Supplies	Number of Magnets
Horizontal Corrector	221	*221 BTP*	221
Vertical Corrector	222	*222 BTP*	222
Quadrupole	291	*574 COTS*	464
Sextupole	81	*121 COTS*	309
Trim Dipole	34	*22 COTS, 10 BTP, 2 COTS&BTP*	747
Main Dipole	1	*3*	747
Total	850	1175	2710

BTP – Built-to-Print

COTS- Commercially-Off-the-Shelf

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Electron Ion Collider



- Polarized Proton Source / Electron Beam Ion source
- LINAC – 200[MeV]
- AGS – Alternating Gradient Synchrotron
  - 0.2 to 20 [GeV]
- HSR – Hadron Storage Ring
  - Protons : 41 -275GeV
  - Superconducting Magnets

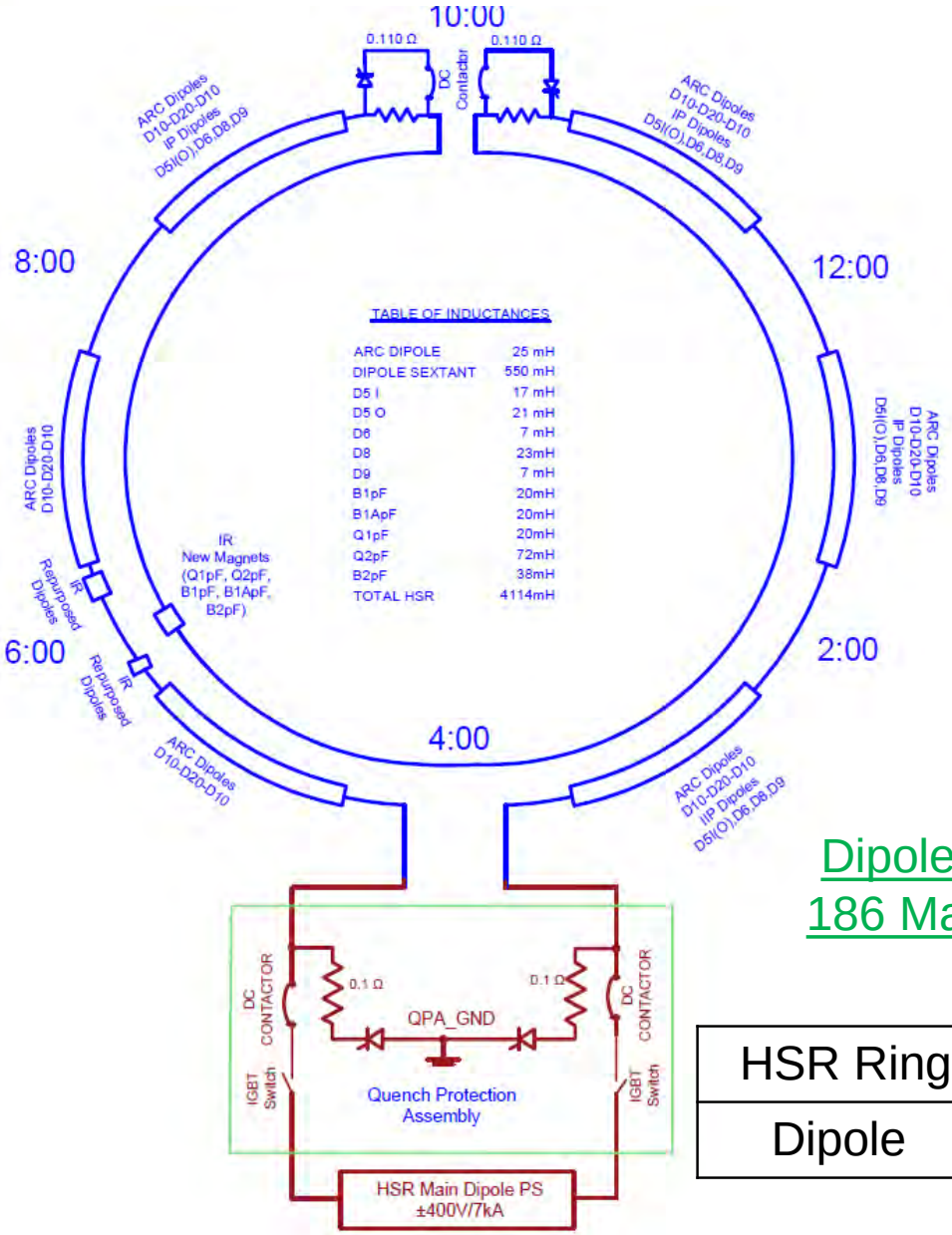
HSR Warm Injection	Number of PS's (New+Existing)
Correctors	53
Quadrupoles	34
Combined Function (CF) Dipoles	2
Dipoles	3
Total	**92**

IR	Number of PS's
Correctors, Skew Quads	47
Quadrupole	33
Spin Solenoid, Rotators, Snakes	11
Dipole	7
Total	**98**

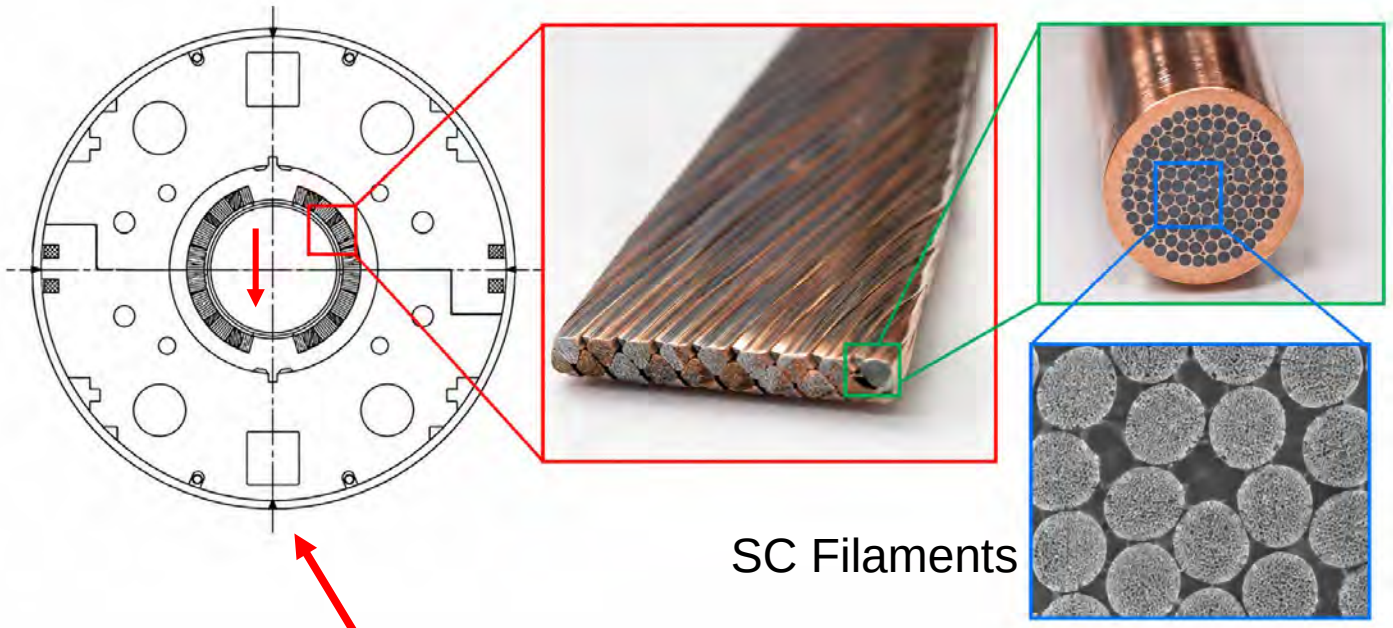
HSR	Number of PS's (New+Existing)
Dipole Correctors, Gamma T's , Skew Quads ,Oct ,Snakes	293
Quadrupoles	110
Sexutpoles	24
Main Dipole, Main Quad, Quad H/V Trim	3
Warm D0 ps's (DWO)	5
Total	**435**

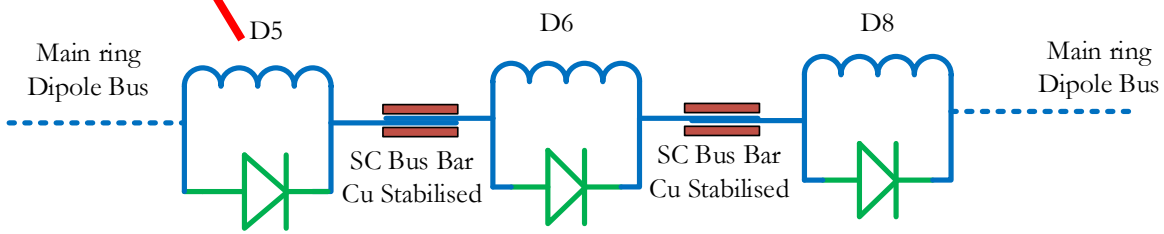
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Hadron Storage Rings – Dipole



Dipole Ring
186 Magnets

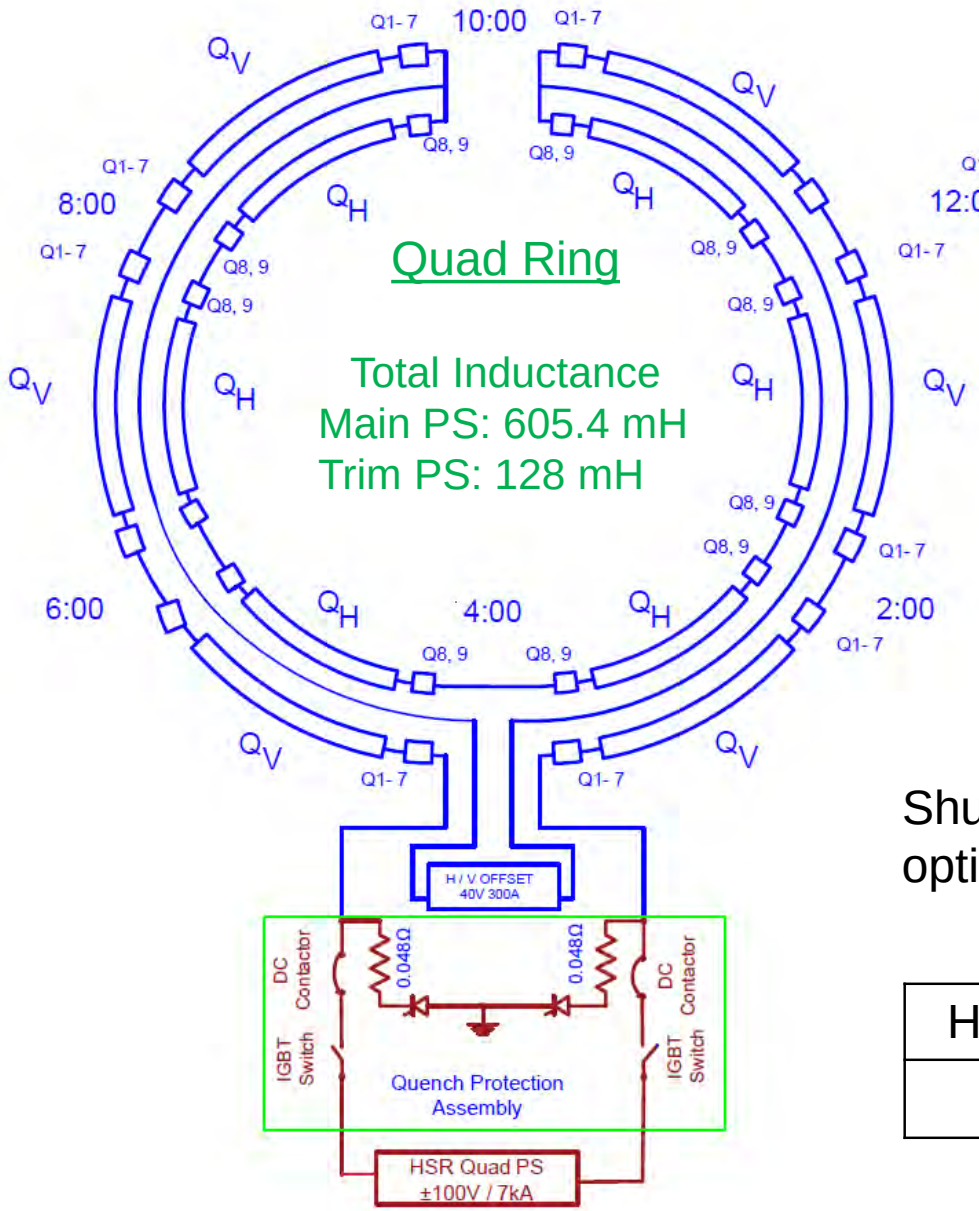


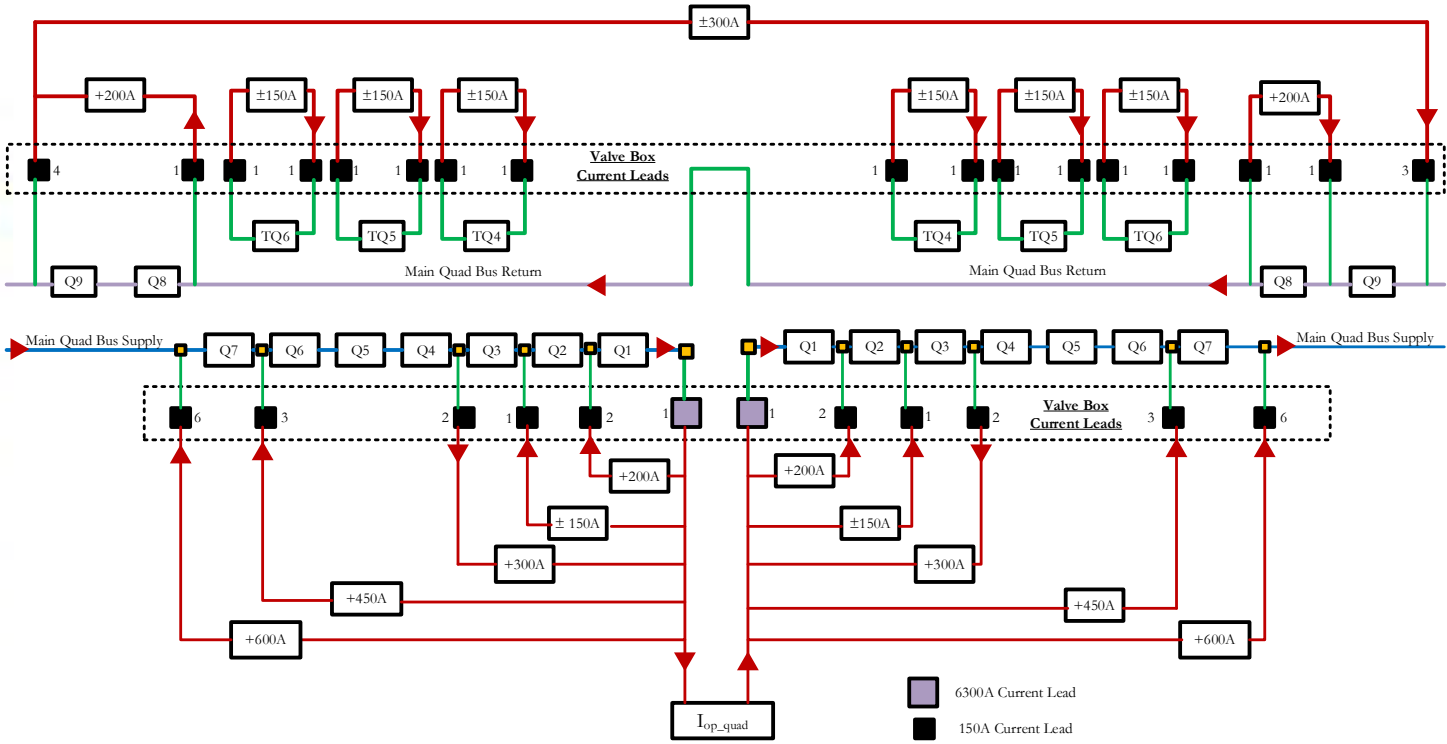


HSR Ring	I_{op}[A]	E[MJ]
Dipole	5760	69.72

- Bypass Cold Diode – Normally do not conduct
- Operating Temperature is at 4.5K

Hadron Storage Rings –Quad





Shunt Power Supplies – Provides more options for controlling the beam

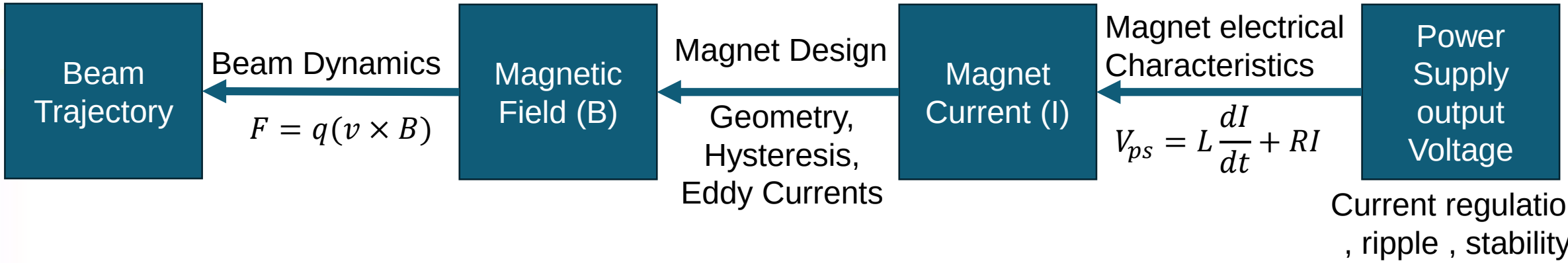
HSR Ring	I_{op}[A]	E[MJ]
Quad	5860	11.47

SC Bus

Cold Crossing Bus

Gas Cooled Leads

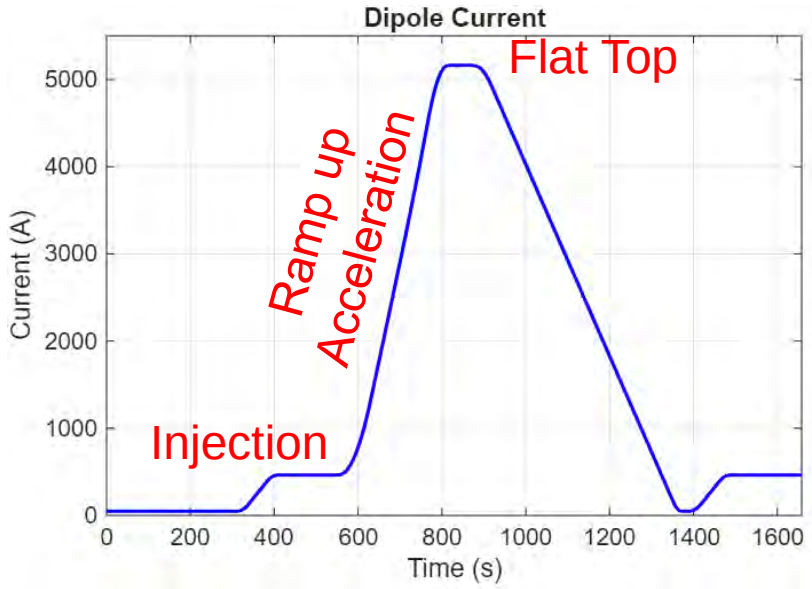
Power Supply Systems for Superconducting Magnets



- The power converter produces the voltage required to establish and regulate the magnet current.
- Magnet current determines the magnetic field; therefore, precise current regulation is essential for controlling the beam trajectory.

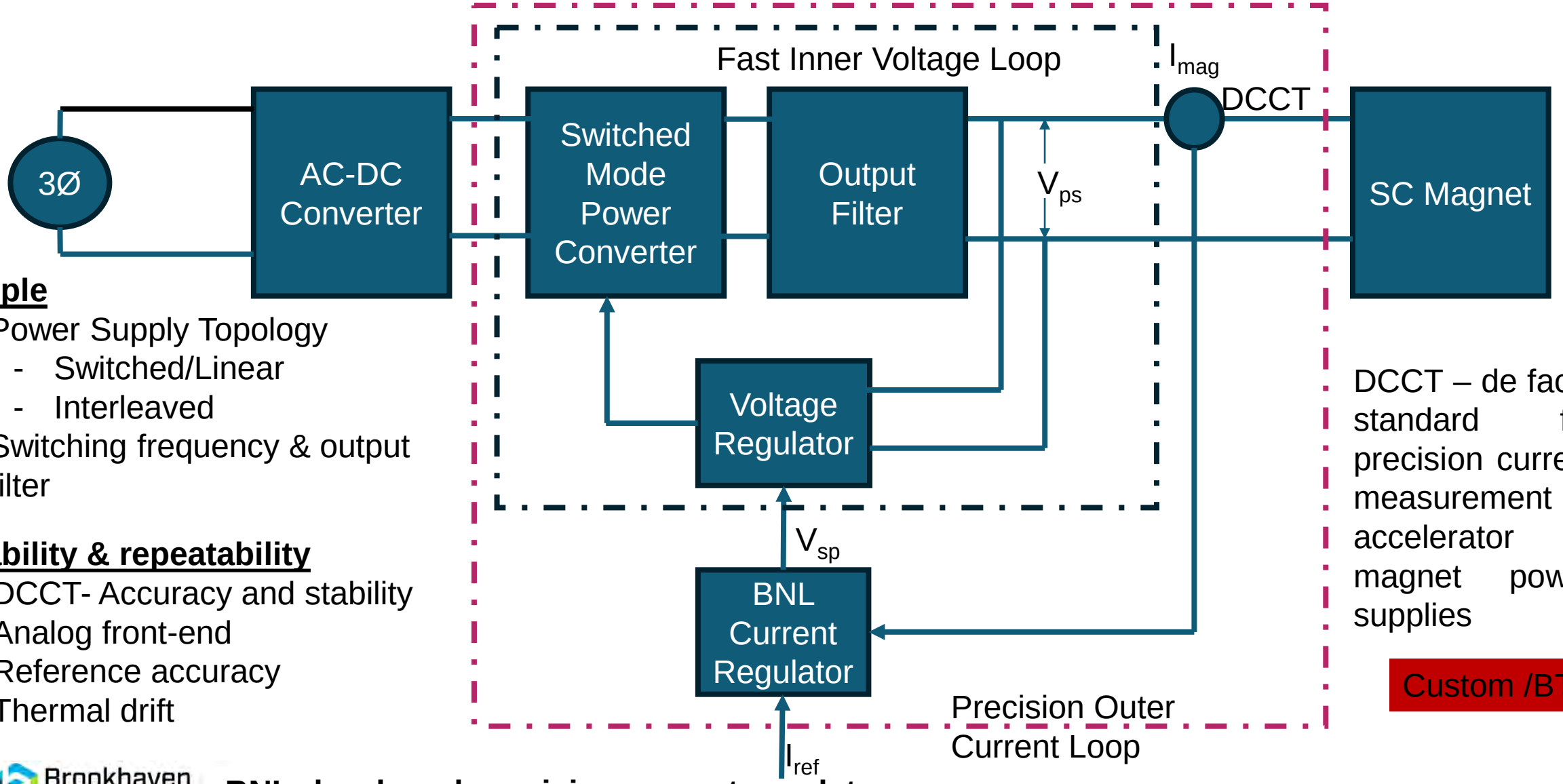
Typical Main Ring Power Supply Requirements

- Current Ripple : <1ppm (6mA in 6000A)
- Current Stability : < 10ppm/hr (60mA in 6000A)
- High reproducibility



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Precision Current-Regulated Power Supply



Ripple

- Power Supply Topology
  - Switched/Linear
  - Interleaved
- Switching frequency & output filter

Stability & repeatability

- DCCT- Accuracy and stability
- Analog front-end
- Reference accuracy
- Thermal drift

DCCT – de facto standard for precision current measurement in accelerator magnet power supplies

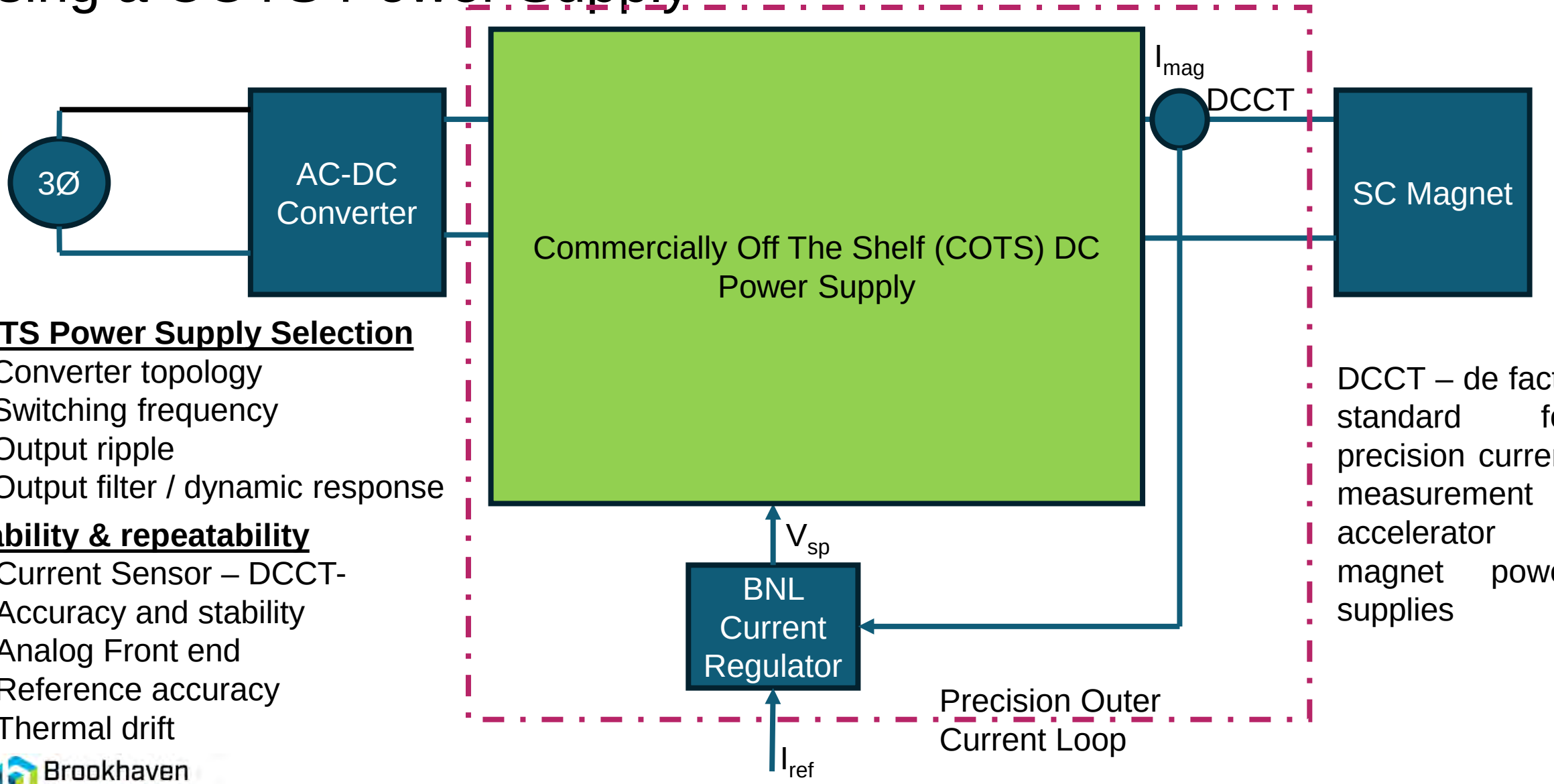
Custom /BTP

BNL-developed precision current regulator

Developed through component selection, characterization, and extensive testing

Precision Current Regulation

Using a COTS Power Supply



COTS Power Supply Selection

- Converter topology
- Switching frequency
- Output ripple
- Output filter / dynamic response

Stability & repeatability

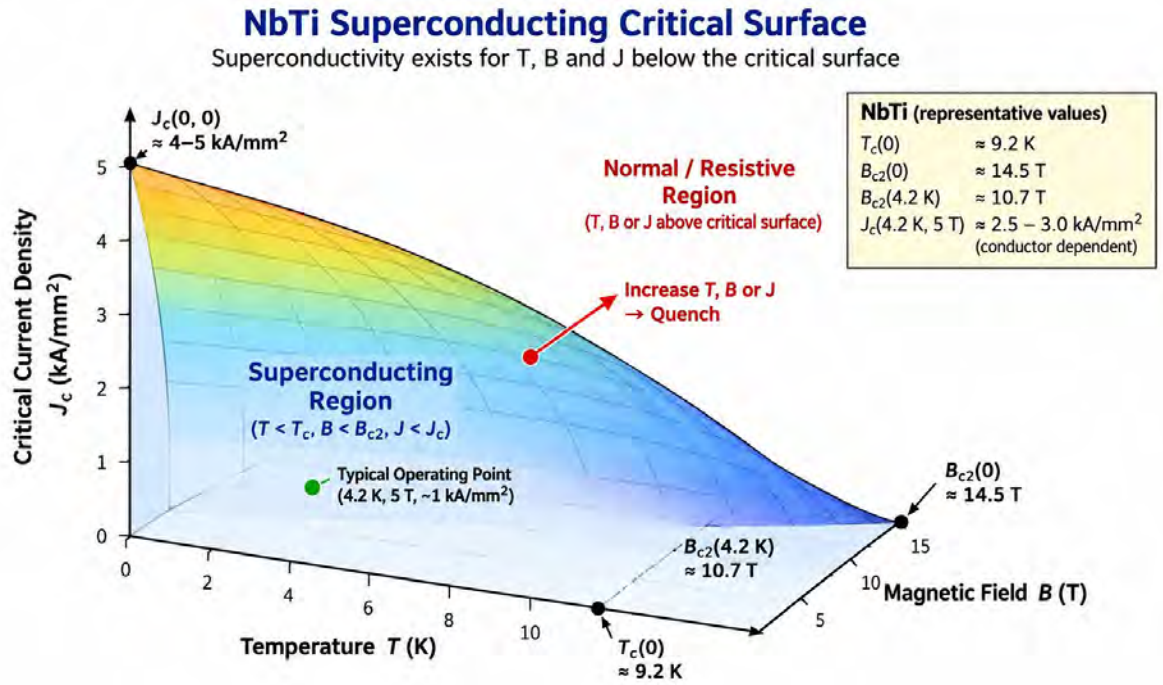
- Current Sensor – DCCT- Accuracy and stability
- Analog Front end
- Reference accuracy
- Thermal drift

DCCT – de facto standard for precision current measurement in accelerator magnet power supplies

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Superconducting Magnets – Critical Surface

- Near-zero DC resistance -> High current density -> Compact, high-field magnets
- Cryogenic operation (4.5K /-451.6ºF)
- Examples of Superconductors
  - LTS : NbTi , Nb_3Sn
  - MTS : MgB_2
  - HTS : ReBCO , BSCCO
- Superconductivity is maintained only while the operating point remains inside the critical surface



Crossing the critical surface due to temperature, magnetic field, or current density causes a transition to the resistive state — a quench

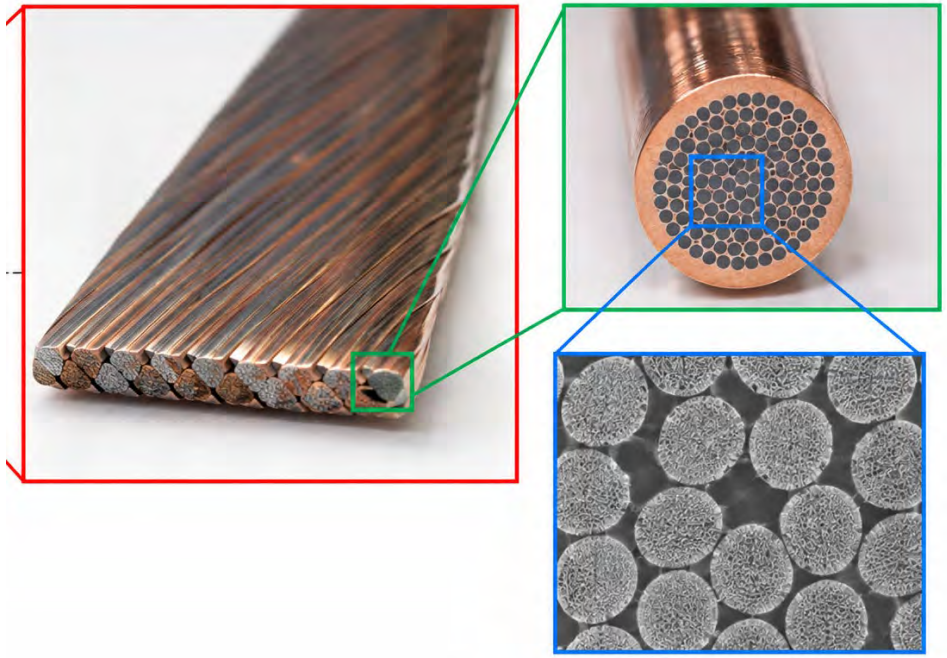
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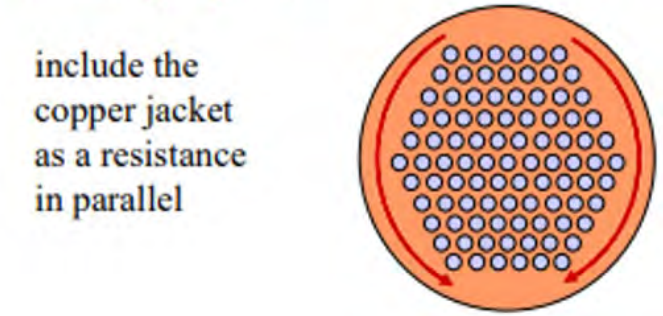
Superconducting Magnets – Composite Wires

- If a local region becomes normal, NbTi develops finite resistance and produces Joule heating

$$P = I^2 R$$

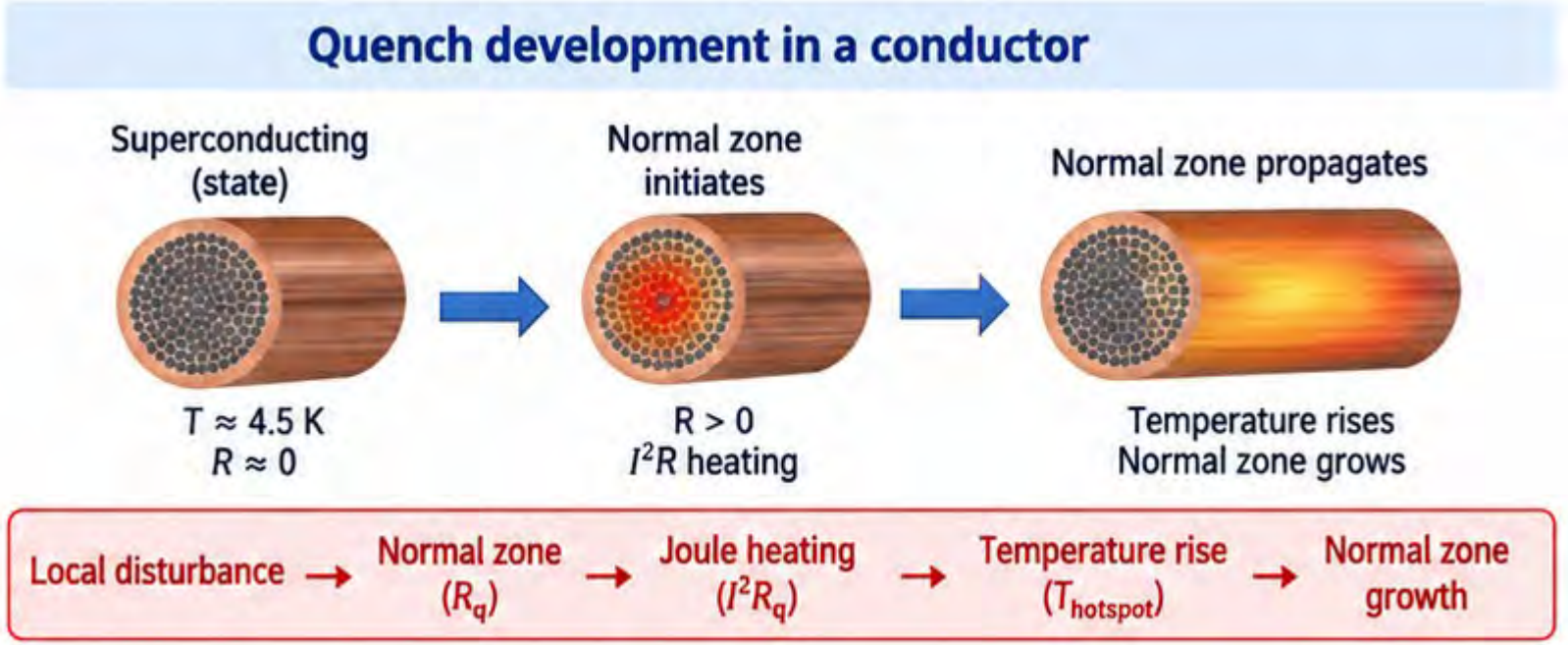
- At cryogenic temperatures (~4.5 K), the heat capacity is very low; therefore, a small energy deposition can produce a rapid local temperature rise.
- **High-conductivity copper is added as a stabilizer**, providing a parallel current path and spreading heat away from the normal zone.
- NbTi is therefore manufactured as fine filaments embedded in a copper matrix; multiple strands form the high-current Rutherford cable

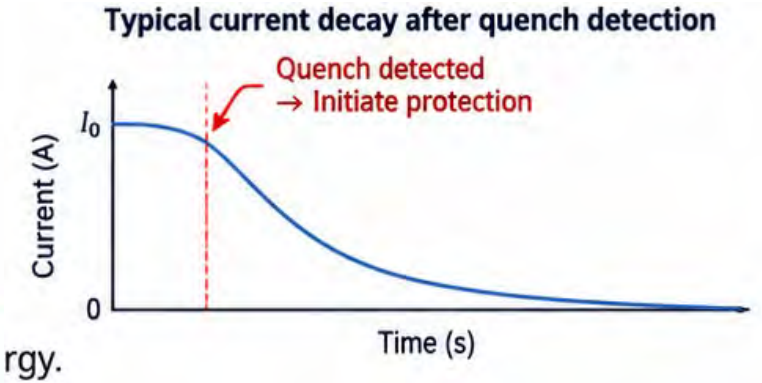




Superconducting Magnets – Quench

$$E_{mag} = \frac{1}{2} LI^2$$





rgy.

- Quench is a local phenomenon – Joule Heating produces hot spot
- Quench protection – How quickly heat propagates and how fast the quench is detected.
- Quench Detection– Voltage sensing –Power supply is disconnected - current in the magnet is made to discharge

Keep Hot Spot Temperature within Allowable limits

Magnet – Inductor – Cannot reduce the current quickly – Keep the voltage within the allowable limits

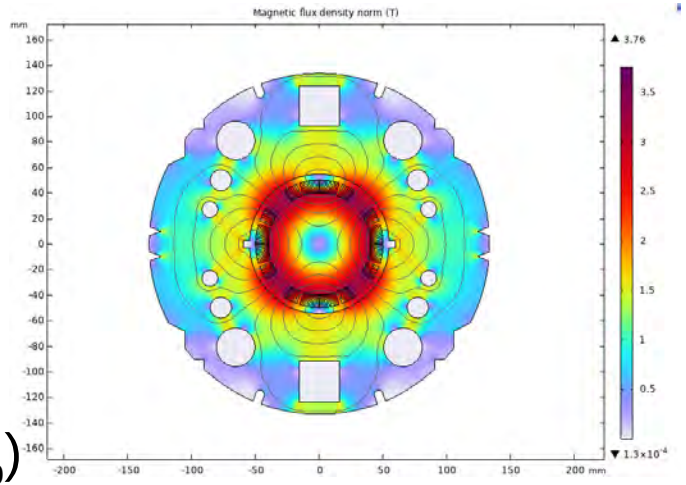
Superconducting Magnet Quench Analysis - PSIM

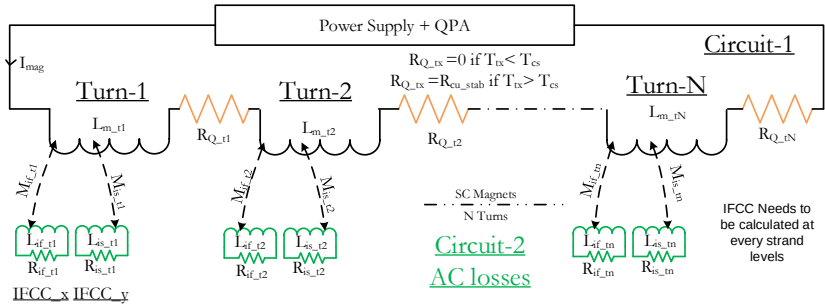
Quench Analysis

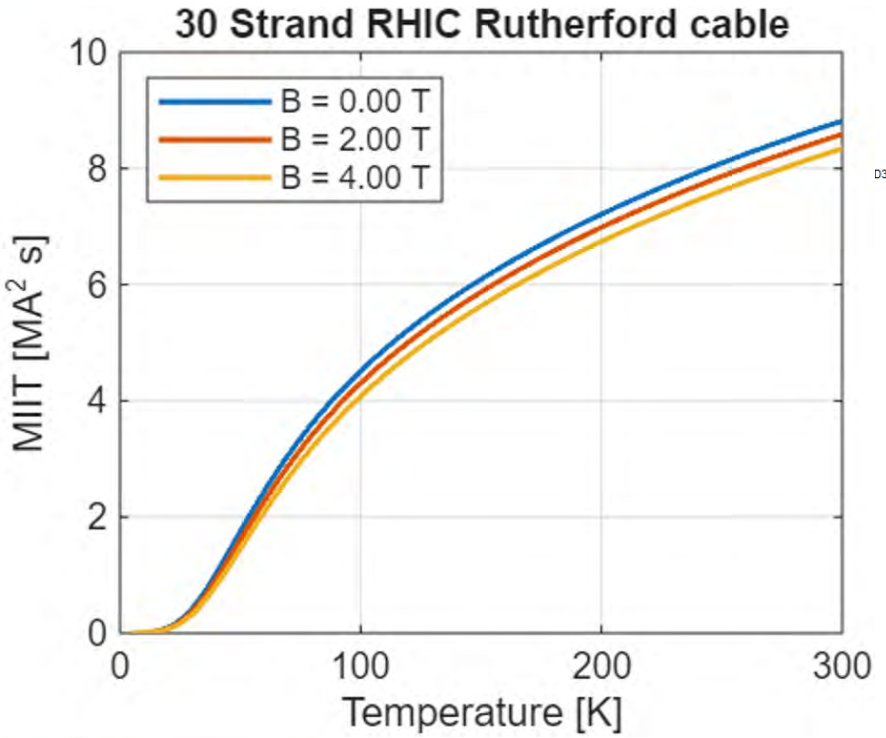
- Estimate the hot spot temperature
- Estimate the Turn-Turn Voltages

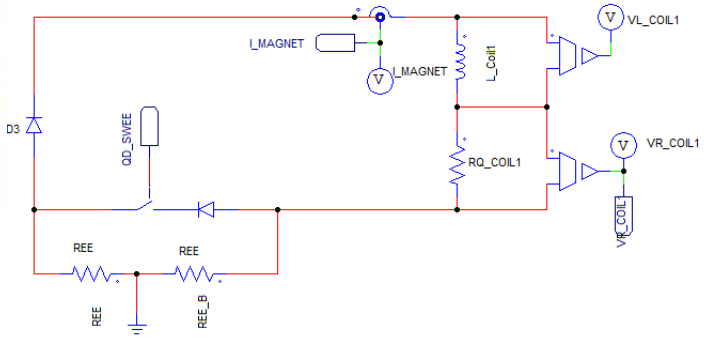
Challenge

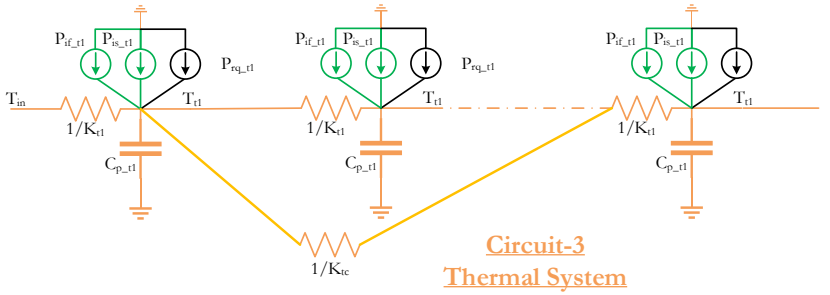
- Coupled Electro-Thermal Analysis
- Highly nonlinear properties (ρ,K,C_p)









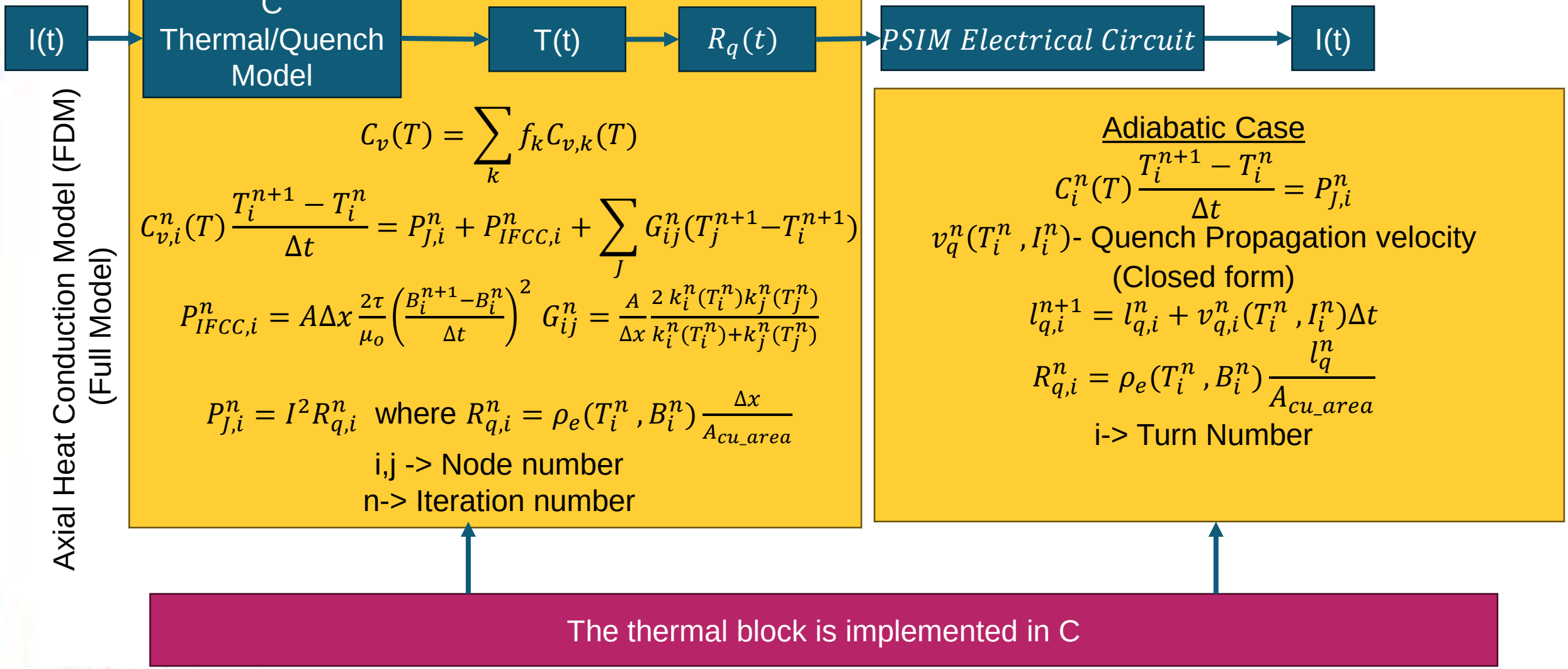


Adiabatic MIITs Equation

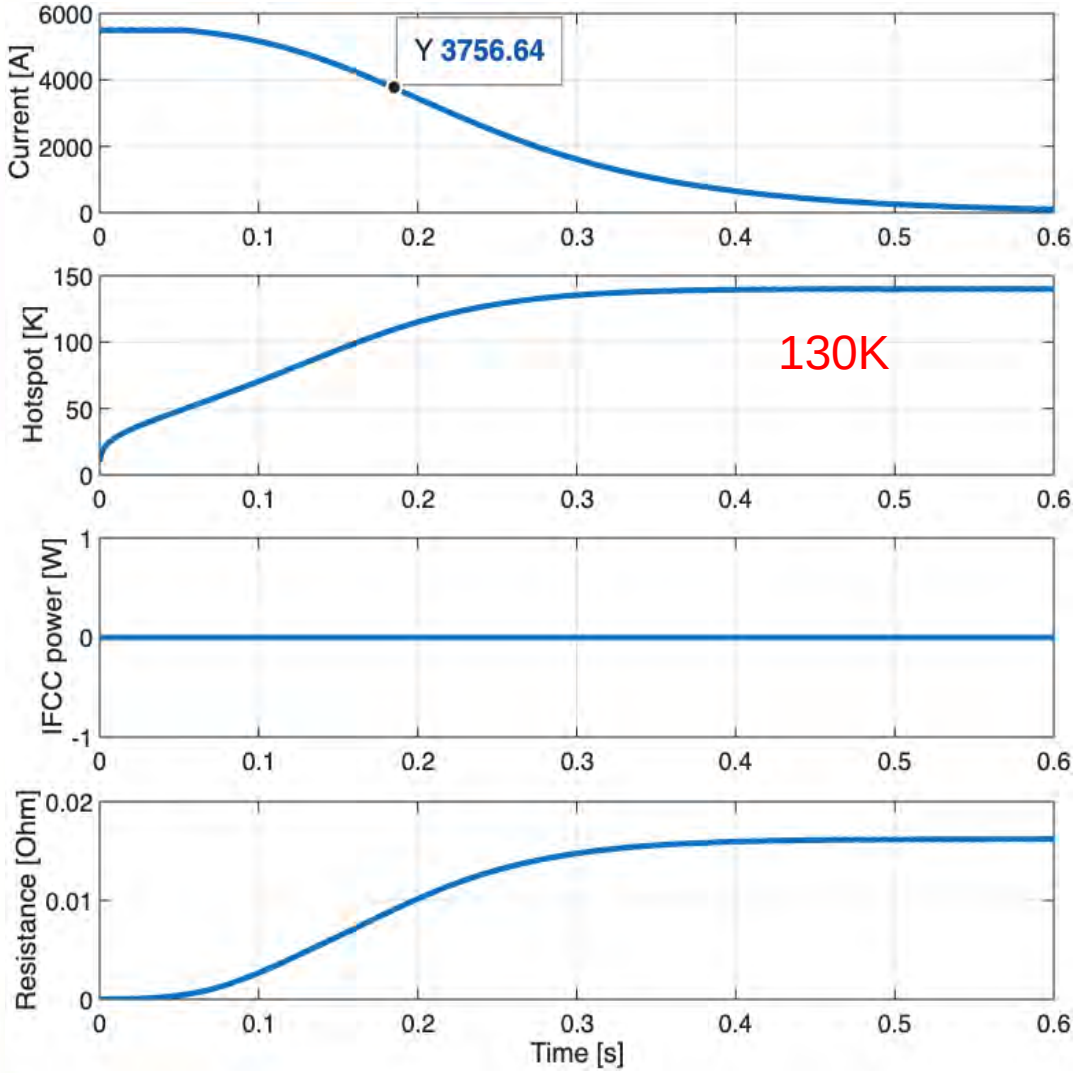
$$\int_0^{\infty} I^2(t)dt = A_{cable}^2 f_{cu}^2 \int_{T_o}^{T_h} \frac{c_{v,cable}(T)}{\rho_{Cu}(T,B,RRR)} dT$$

- MIITs means Mega-Ampere²-seconds
- Is a convenient measure of the thermal burden imposed on the conductor during the current decay

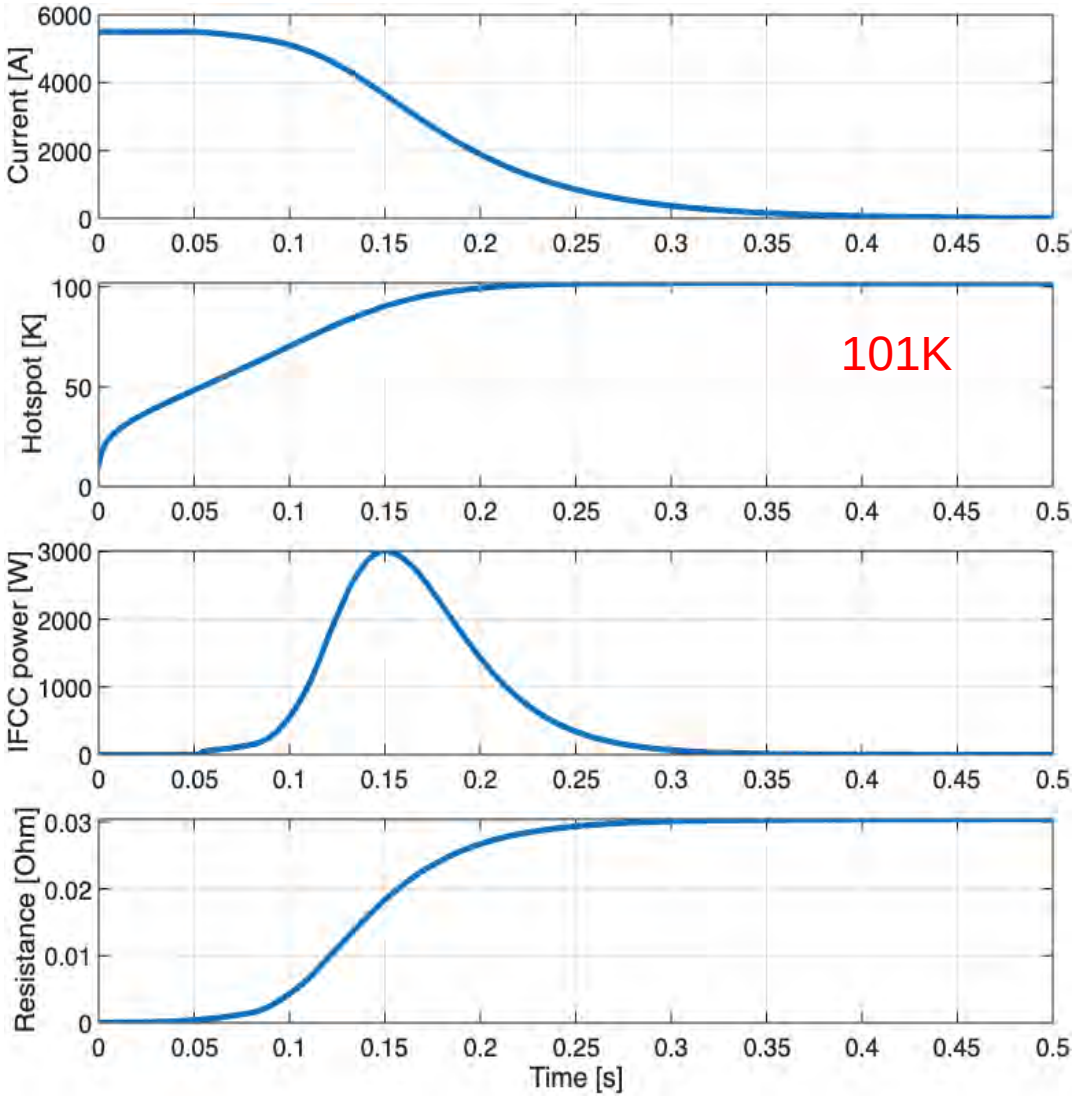
Quench Analysis methodology



Superconducting Magnet Quench Analysis – PSIM (Adiabatic with IFCC effect included)

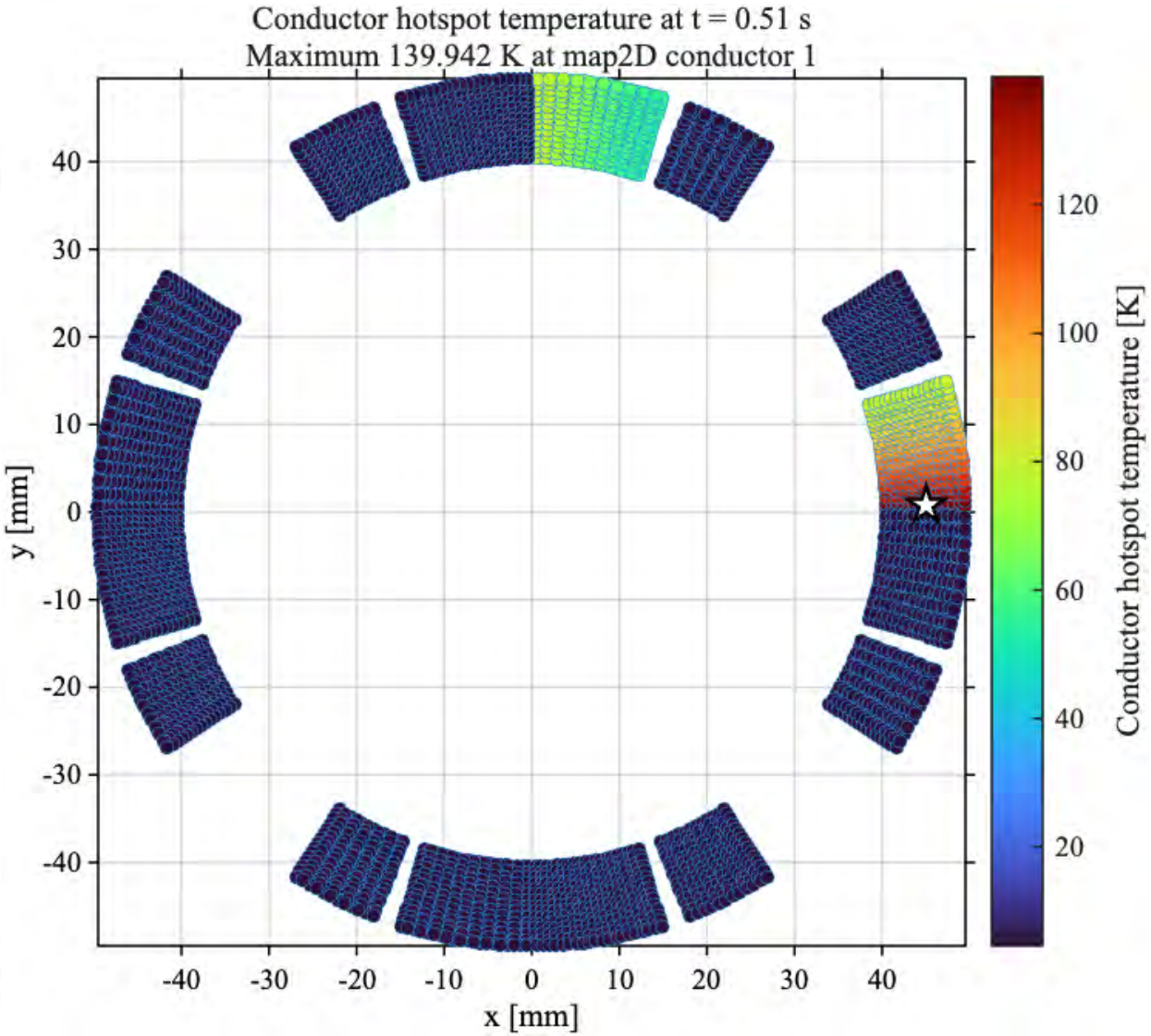


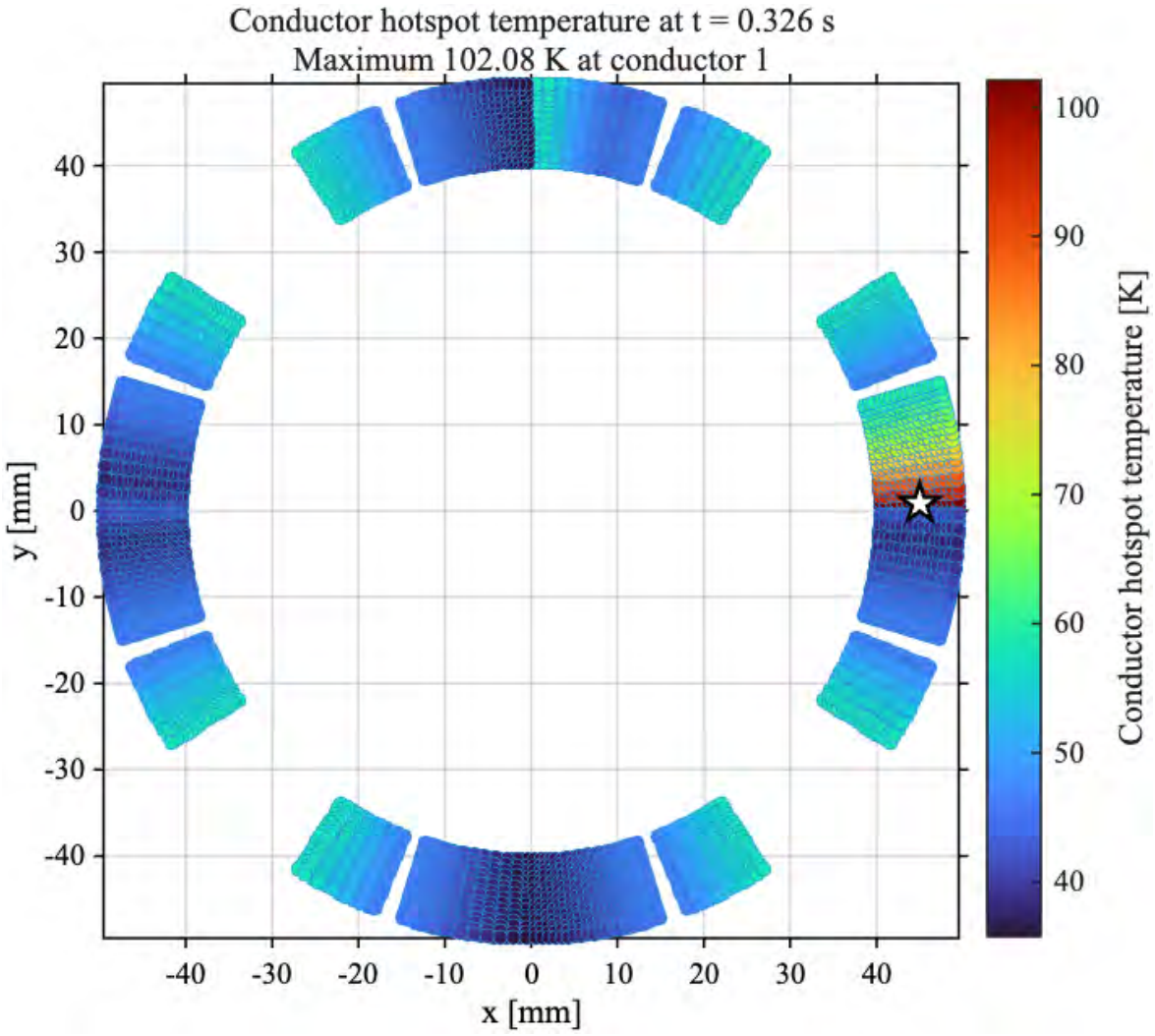
Adiabatic with turn-turn contact



Adiabatic with turn-turn contact + IFCC

Quench Protection Analysis – Q4 Magnet

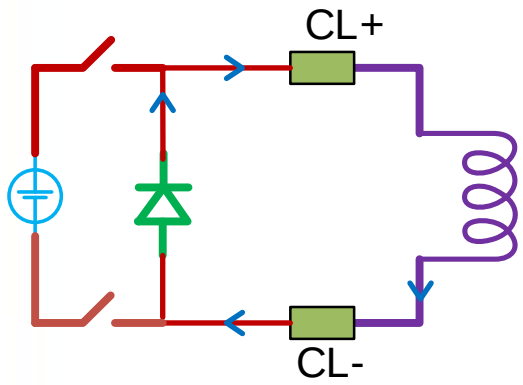




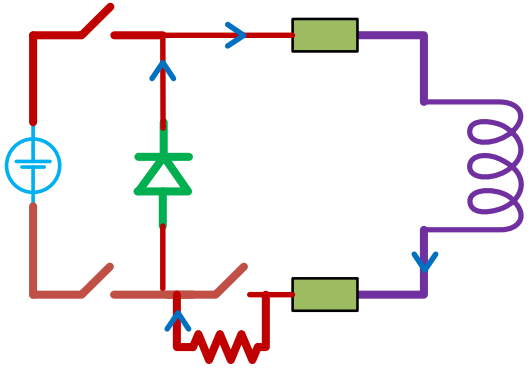
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Superconducting Magnet Quench Protection Methods

- **Self-protection** — magnet's own resistance growth dissipates the stored energy
- **External energy extraction** — dump resistor extracts energy from the magnet circuit
- **Quench heaters** — deliberately initiate and spread the normal zone
- **CLIQ – Coupling-Loss Induced Quench** — induces coupling losses to rapidly distribute the normal zone
- **ESC – External Secondary Coupled** — inductive coupling to an external secondary winding promotes distributed quenching.

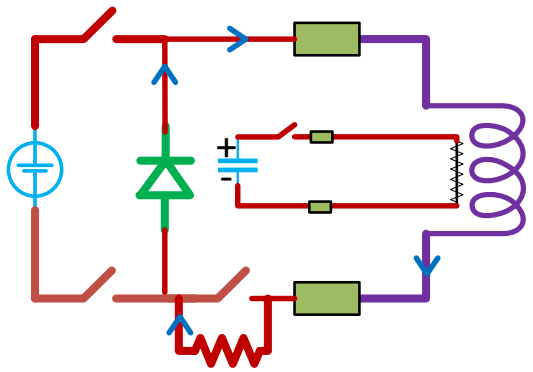


Self Protection



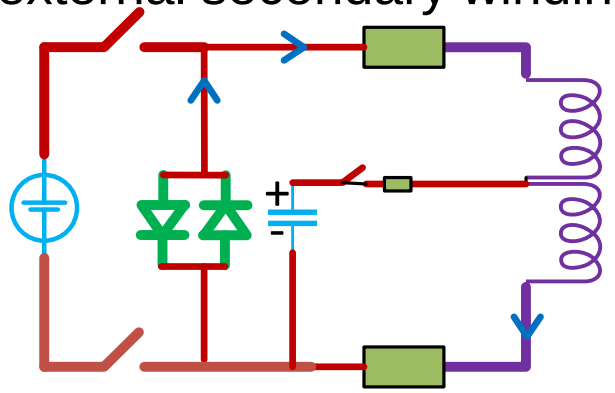
External Energy Extraction

R_{ee} ↑ $T_{hotspot}$ ↓ V_{mag} ↑

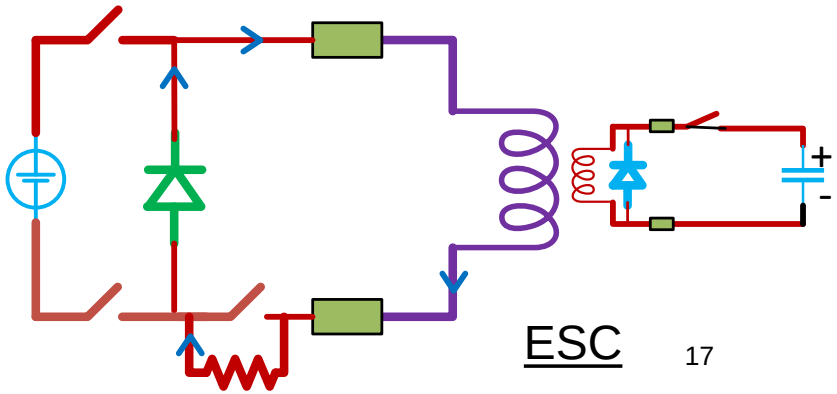


Quench Heaters

- *Rapidly spread the normal zone*
- *Requires heater-to-coil electrical insulation*



CLIQ

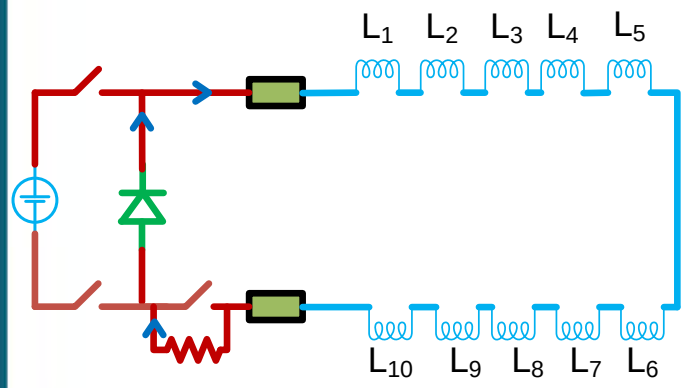


ESC

Quench Protection of Series Connected Accelerator Magnets

HSR : 186 Series-Connected Magnet, Circumference: 3.3 km

Series Connected Magnet String



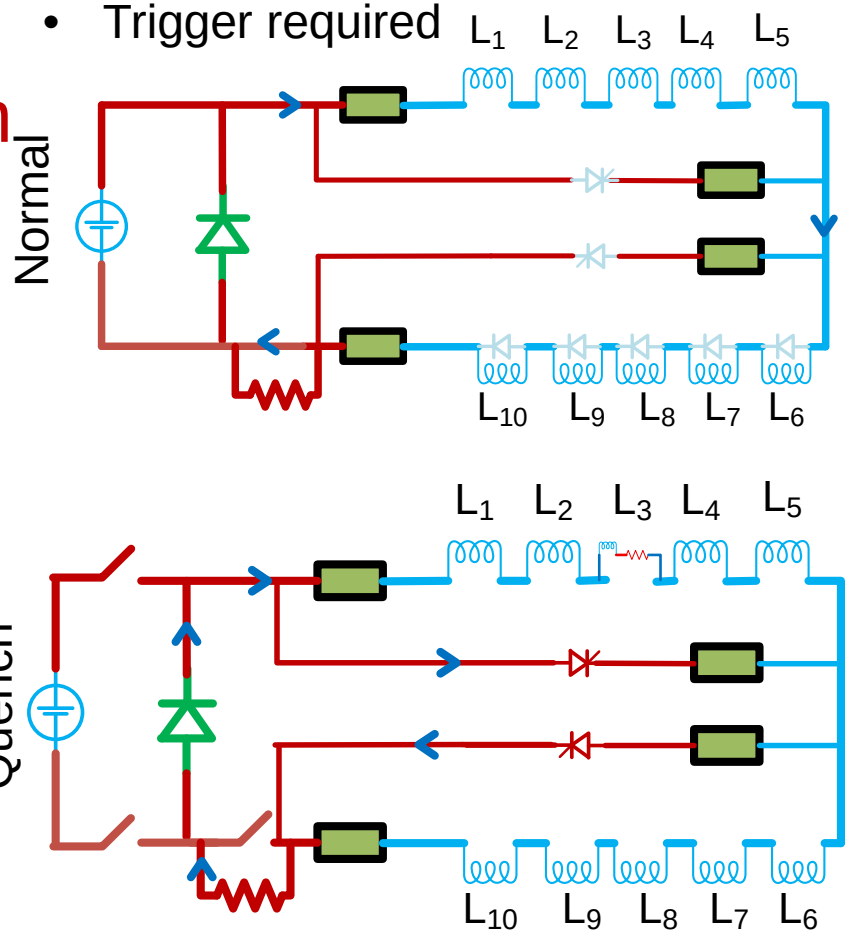
L_x=25mH L_{tot}=250mH

L_{HSR_Dipole}=4.16H

Active Bypass – SCR/Thyristor

Tevatron

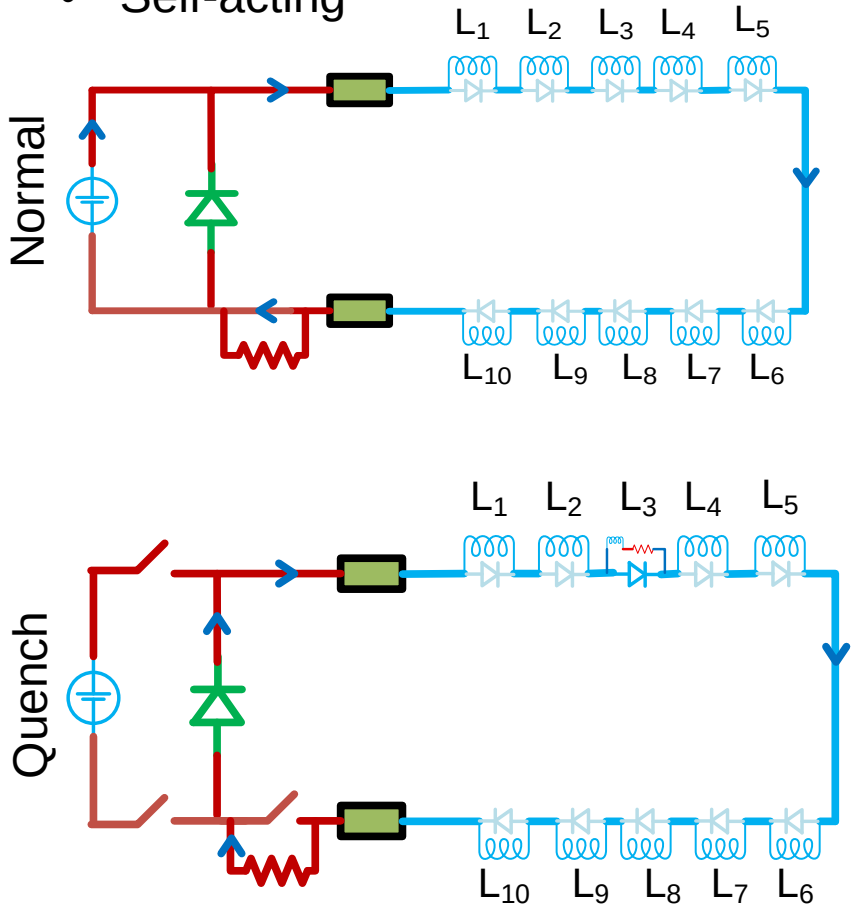
- External Switch
- Trigger required



Passive Bypass – Cold Diode

RHIC/ HSR

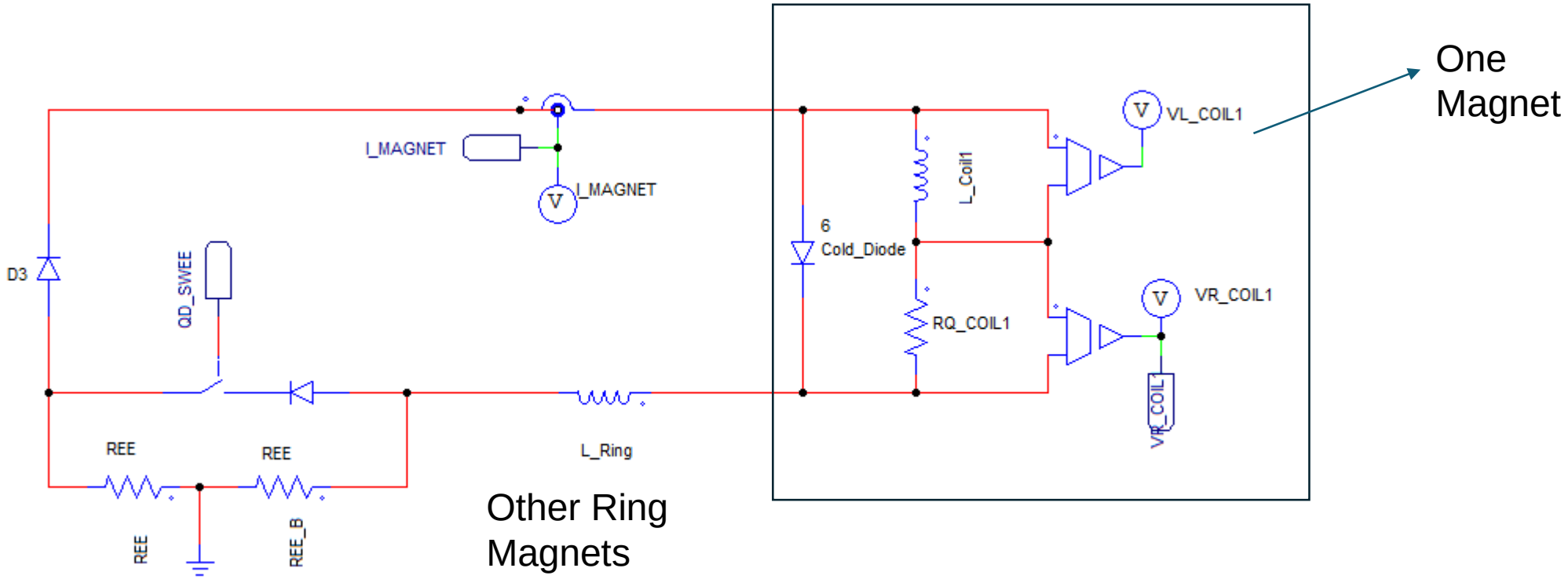
- Local Cryogenic bypass
- Self-acting



Fundamental Requirement : Alternate high current path around the quenched magnet/cell

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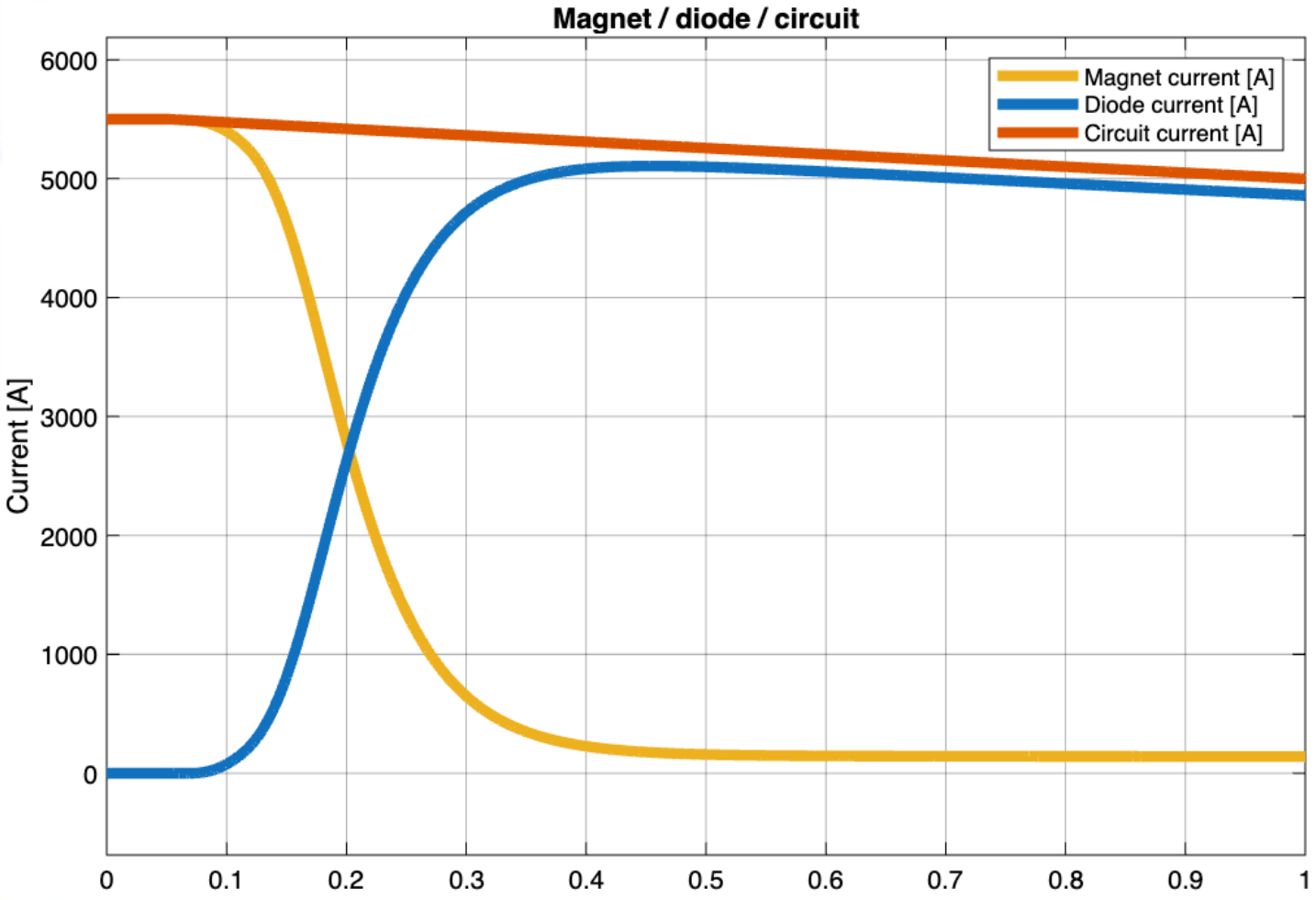
Quench Protection of Magnet in HSR Ring – Bypass Diode

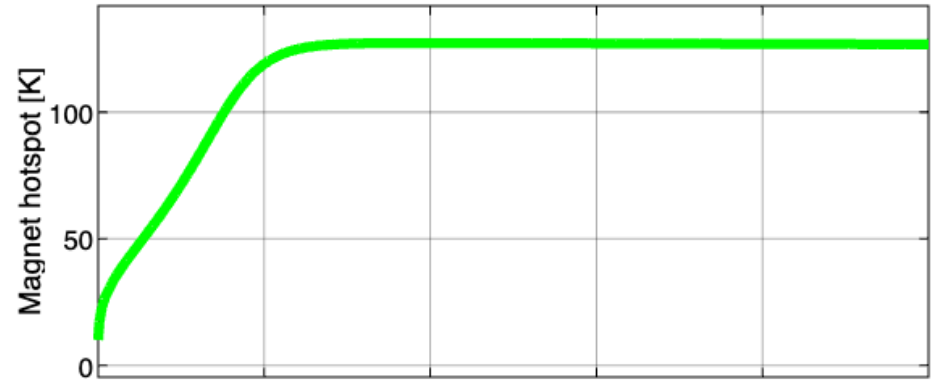


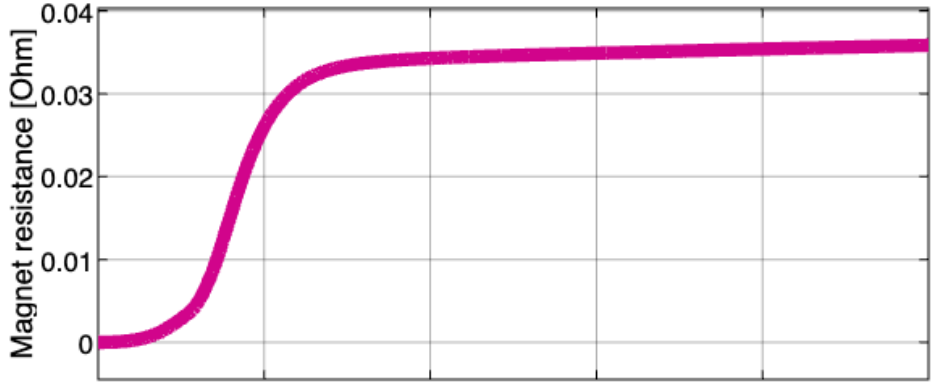
Only Change in the Electrical Protection Circuit
No Change in the Thermal and IFCC Modules/Functions

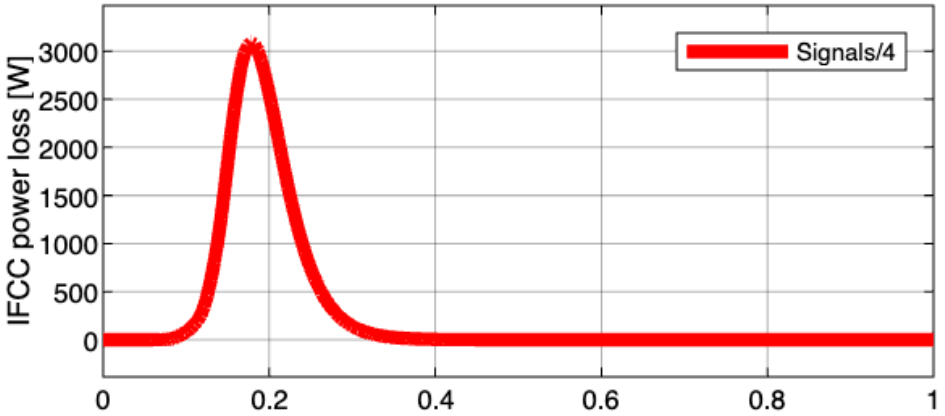
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Quench Protection Analysis - Results



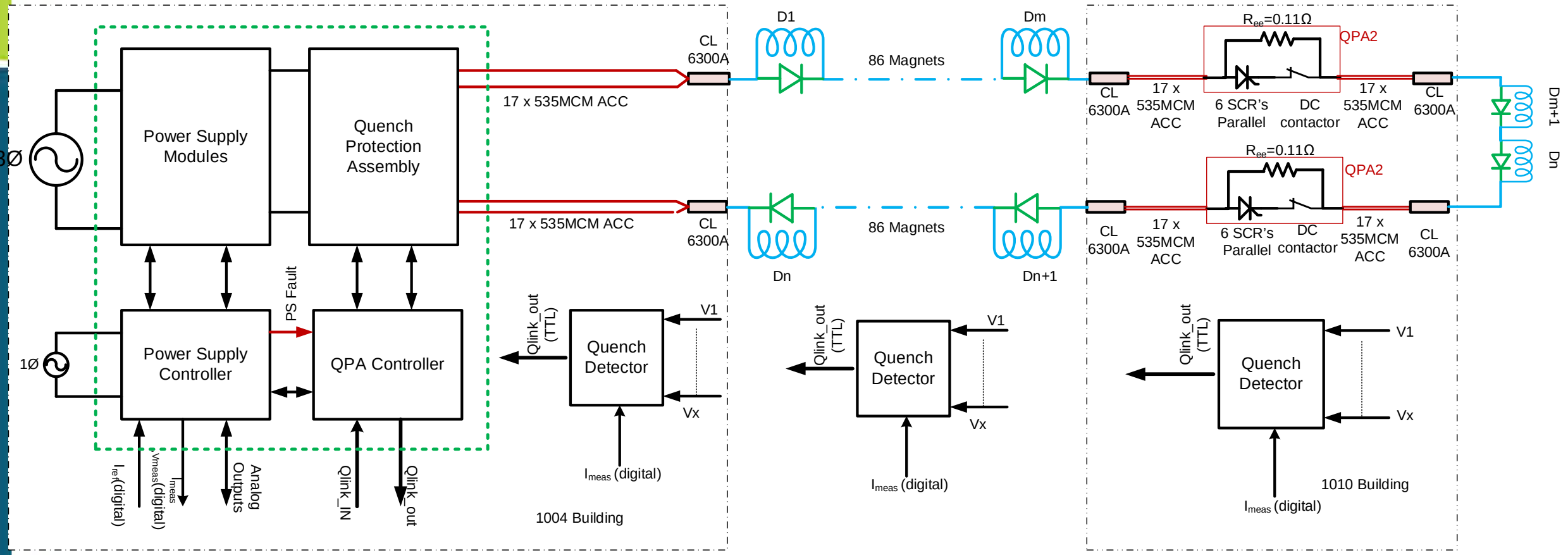






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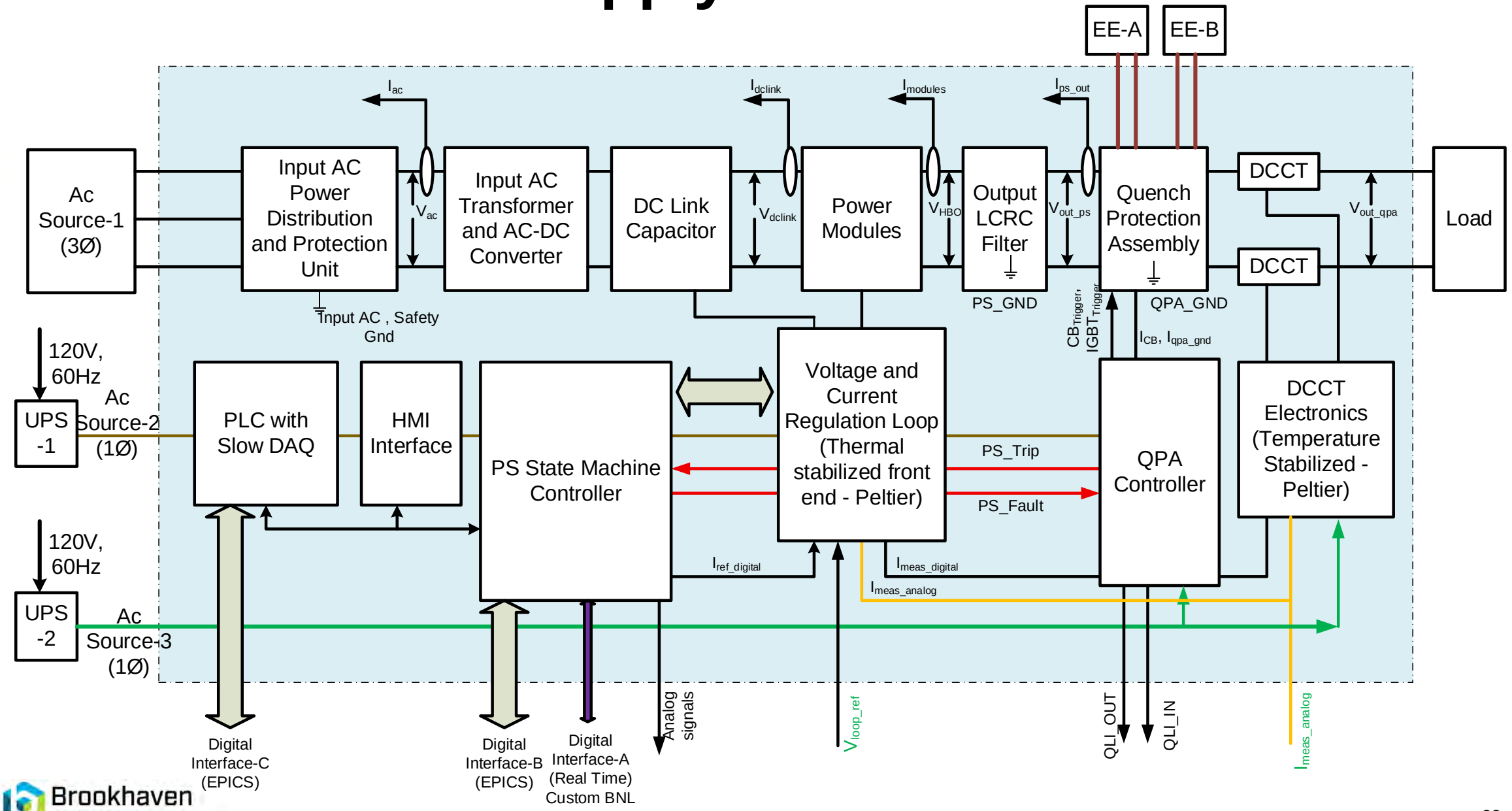
HSR Dipole Power Supply



Quench Detection System

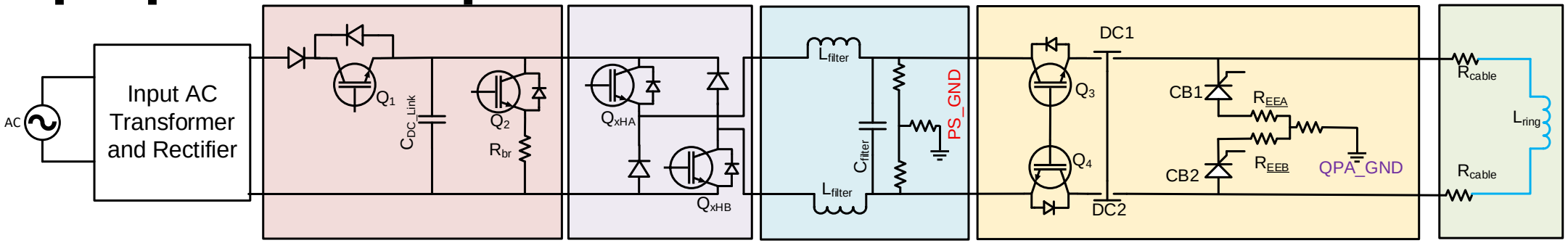
- Distributed in each service building throughout the ring
- $V_{quench} = V_{mag} - L\frac{dI}{dt}$

HSR Main Power Supply Architecture

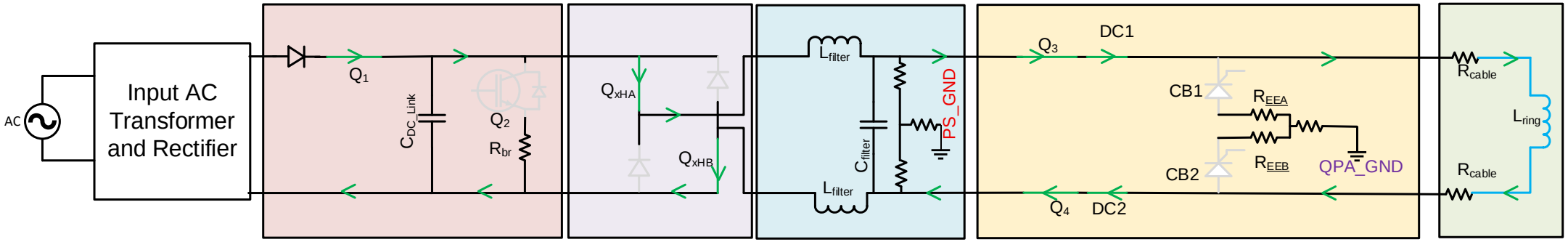


PS Architecture

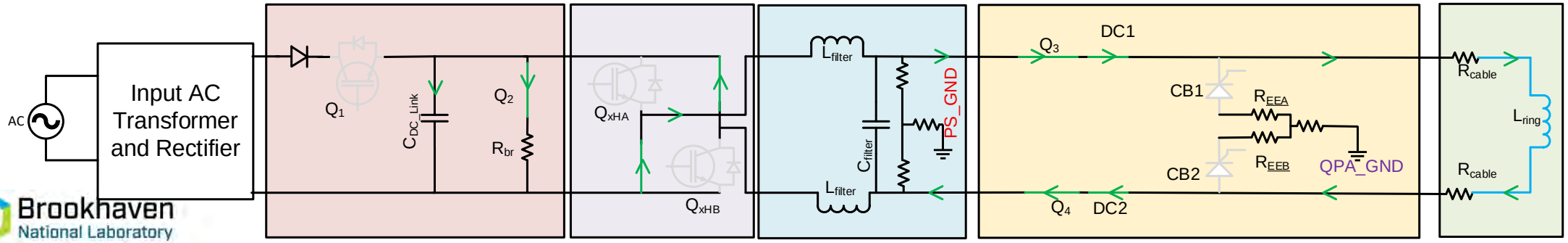
MMPS Operating Sequence
Ramp up and Ramp down



Ramp up and steady state

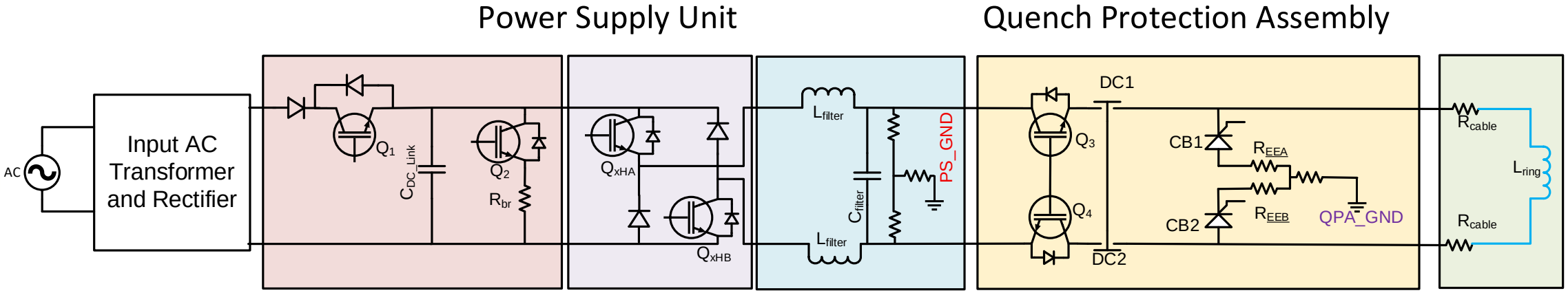


Ramp down



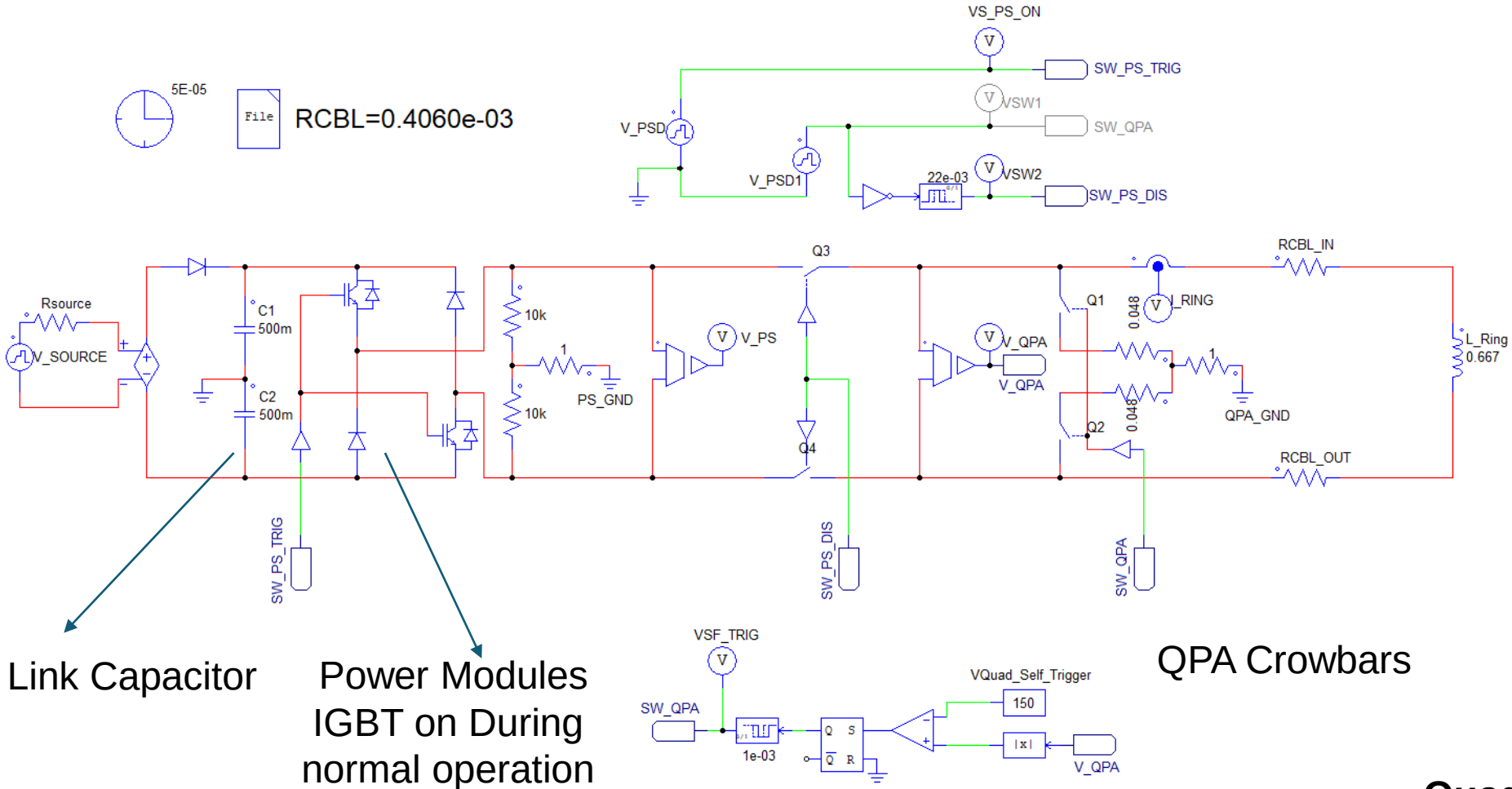
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MMPS operating Sequence –Quench / Fault



- The IGBT Q3 and Q4 along with DC Contactor are critical. They should never open during normal operation before crowbar is fired.
- In the event quench
  - Step-1: The quench link is pulled down by the quench detectors.
  - Step-2: The QPA controller waits for 10ms (configurable) for the beam abort to be completed.
  - Step-3: The trigger pulse to power supply unit half bridge is removed and then the crowbar gates are triggered.
  - Step-4: After 1-2ms delay of crowbar triggered , IGBT Q3 and Q4 , triggers are removed. IGBT must interrupt the power supply current within 20ms.
  - Step-5: After 20ms (Configurable) , the DC contactors are deenergized. If IGBT has interrupted the current , the DC contactor opens at near zero current
  - Step-6: If IGBT's did not interrupt the current , the DC contactors will interrupt the power supply full output current (Worst case. This time must be less than 120ms)

Self Trigger Circuit



DC Link Capacitor

Power Modules IGBT on During normal operation

QPA Crowbars

Self Triggering Circuit set to 150V (Latched)

Quad Power Supply

Self-Trigger Circuit - Results



Current through the magnet

Voltage across the magnet Ring

VS_PS_ON – Power supply PWM pulse/IGBT Switch
VSW1 – Crowbar Trigger pulse (Delay 10ms)
VSW2 – PS Disconnect Switch (Delay 22ms from VSW1)

DC Link Capacitor Current

DC Link Capacitor Voltage

Current through EE Resistor

Grounding of a Floating Magnet Power Supply

Why a floating power supply?

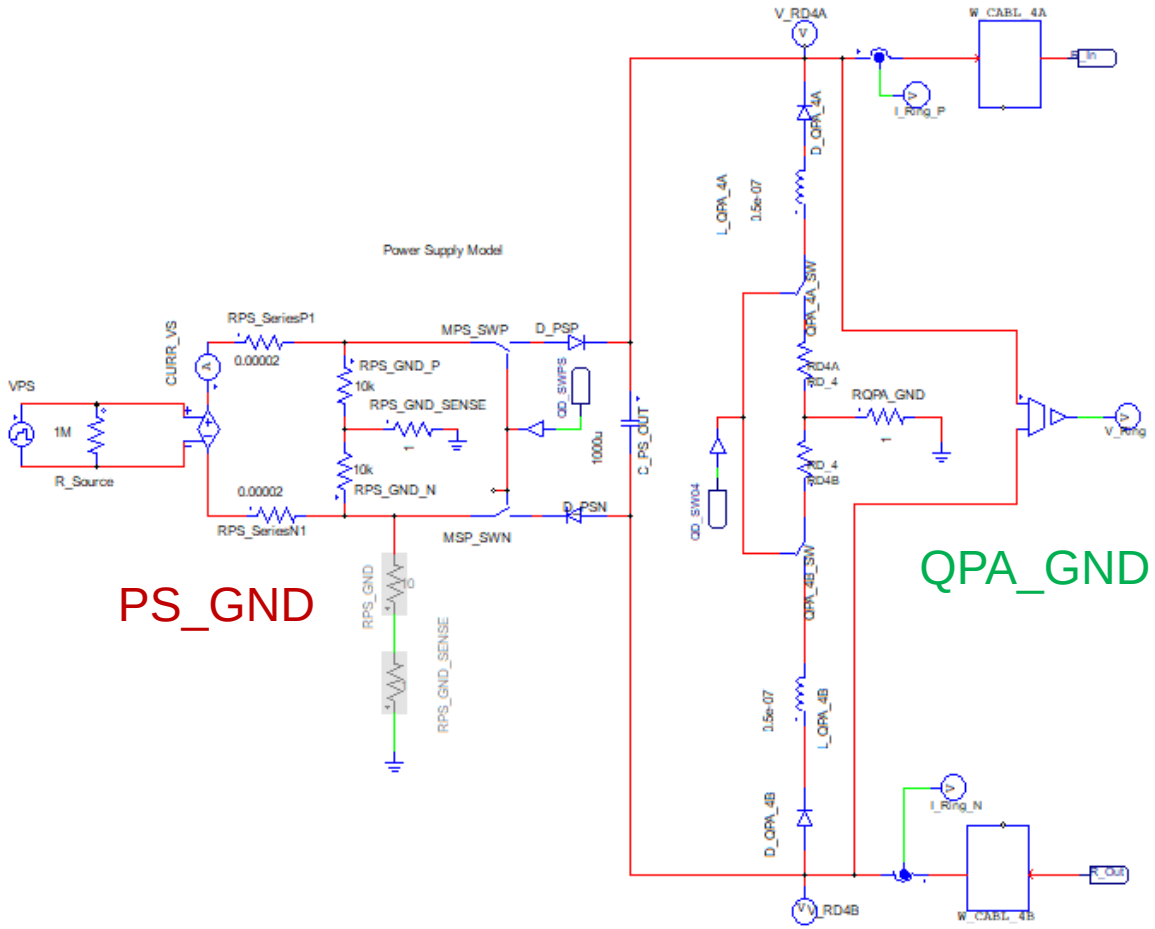
- Neither output terminal is directly connected to ground.
- Allows the magnet circuit voltage-to-ground to be managed independently of the differential magnet voltage.
- Helps with insulation coordination and ground-fault management.

Why ground a floating magnet circuit?

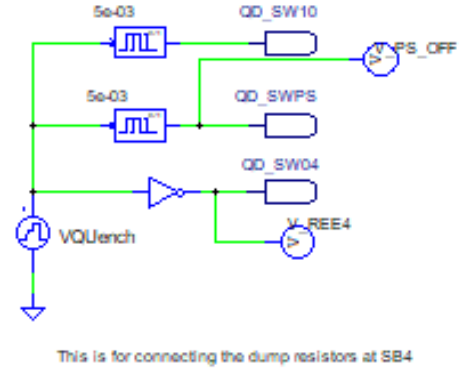
- A completely floating circuit can develop an uncontrolled common-mode potential relative to ground.
- A controlled grounding/monitoring network:
  - establishes a defined voltage reference to ground
  - enables ground-fault detection
  - supports personnel and equipment protection

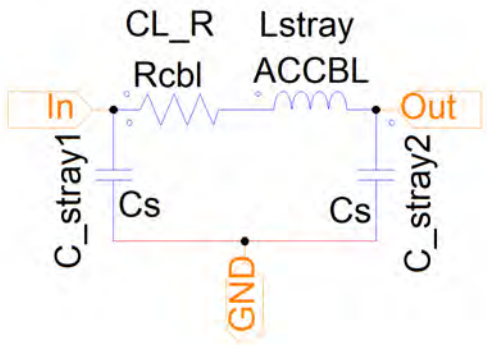
Grounding configuration influences both fault current and magnet voltage-to-ground

HSR Dipole Ring – Simulation Model

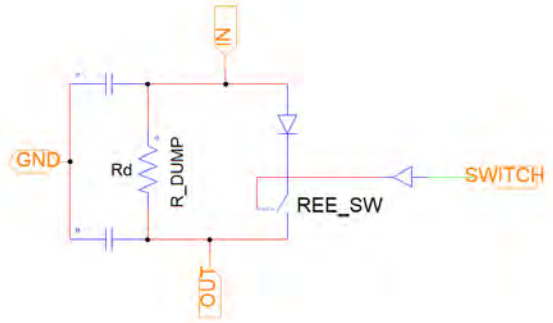


Magnet String

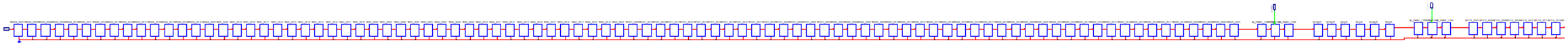




Cable model

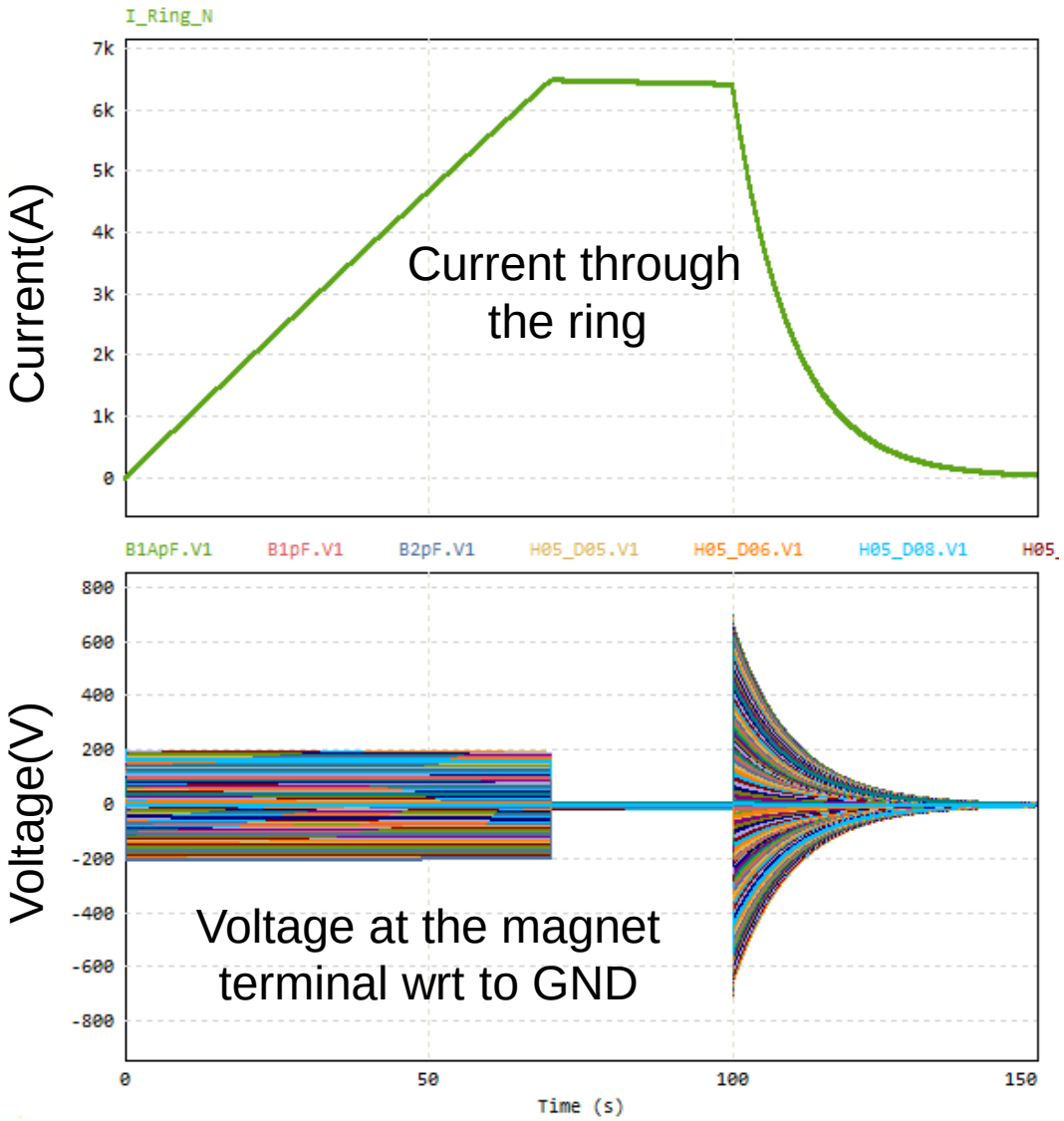


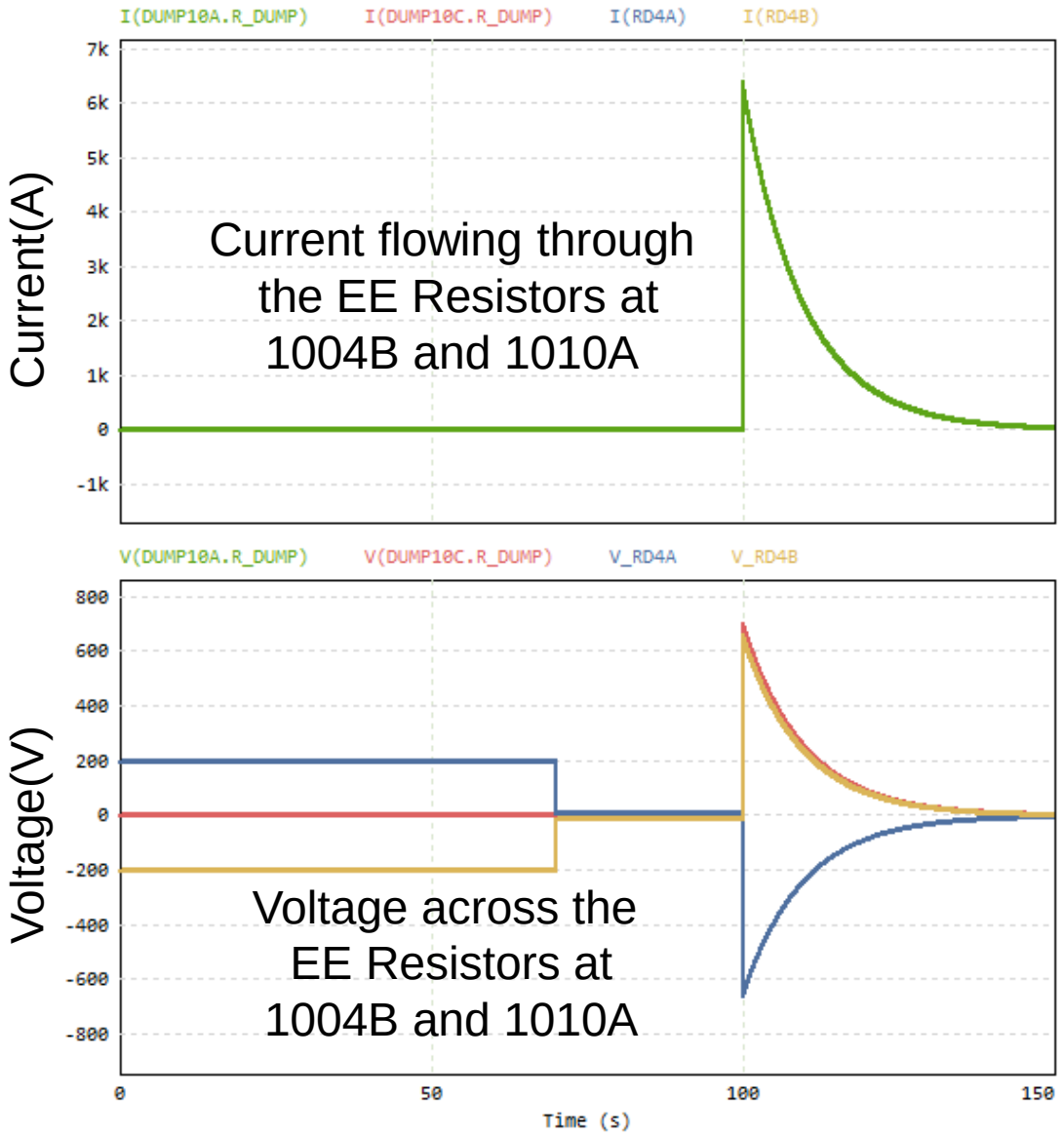
QPA model



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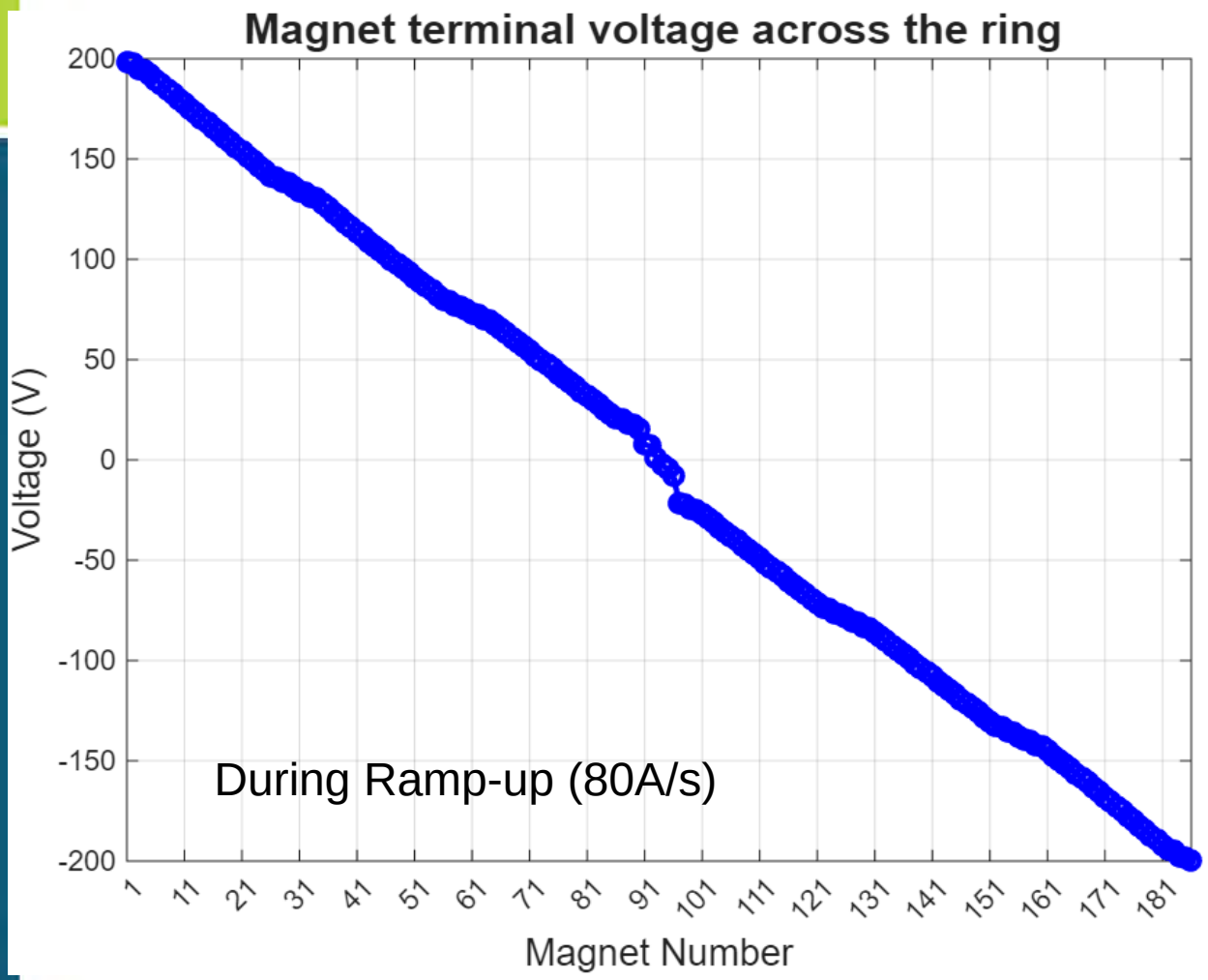
Simulation Results

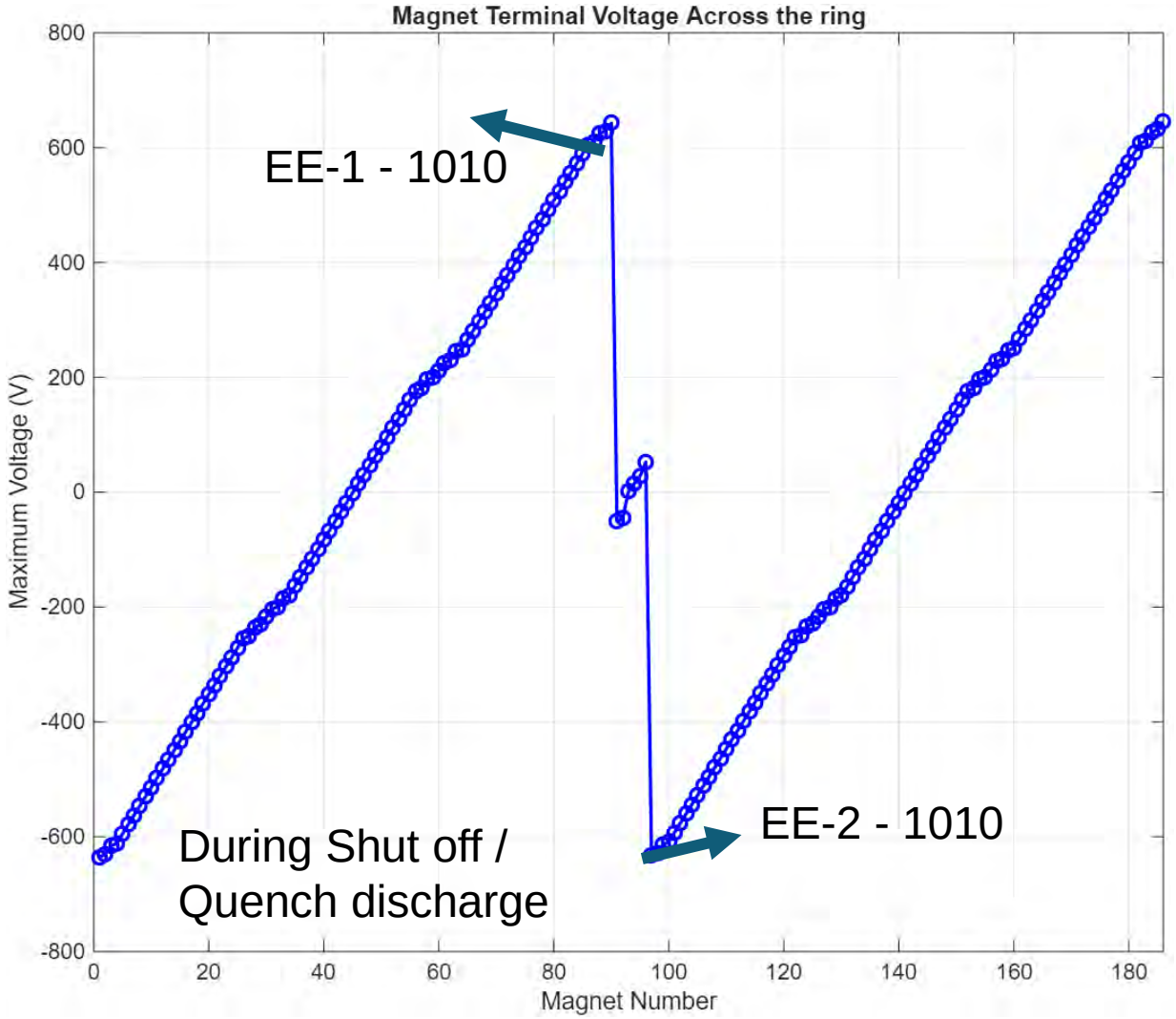




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Voltage Across the Ring



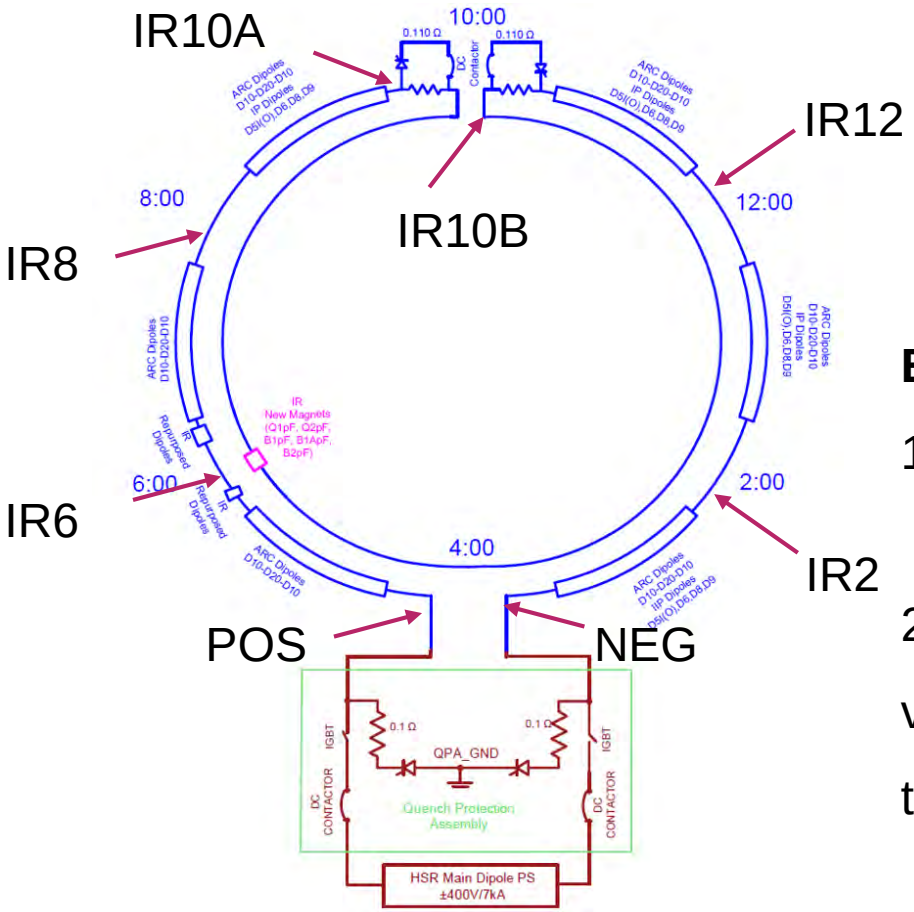


Peak Voltage : 673V

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Ground Fault Analysis

Evaluate the impact of ground fault location and grounding configuration on fault current and voltage distribution

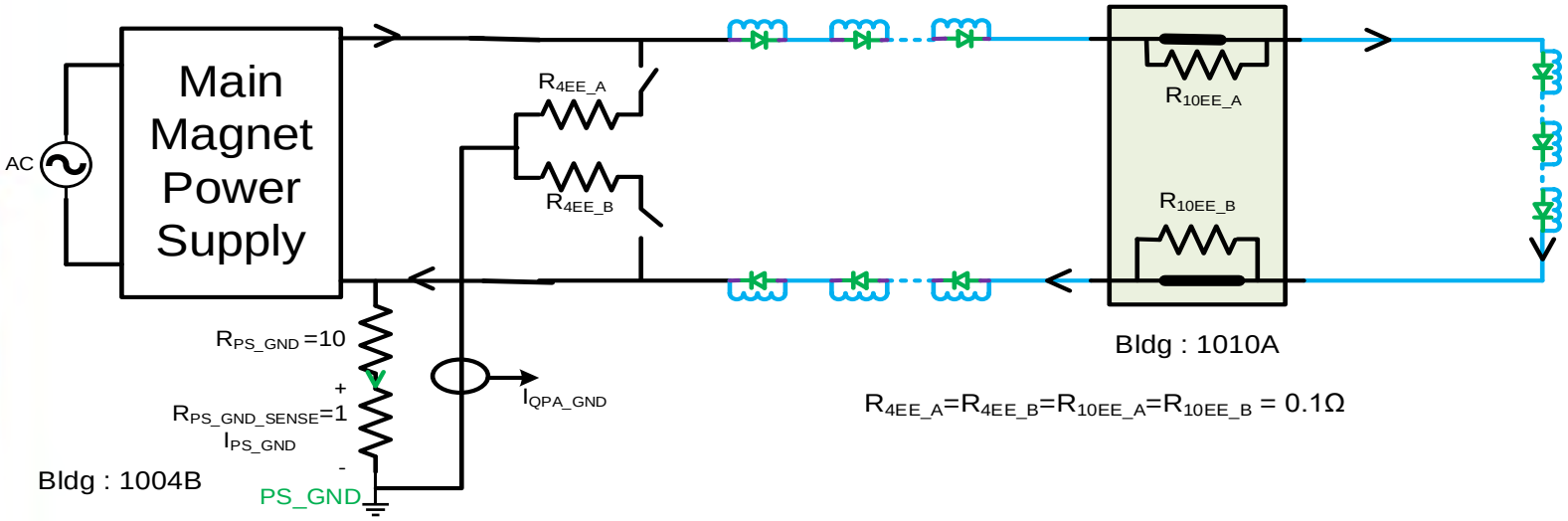


Parameter	Cases Considered
Fault Location	All IR locations , Power Supply/QPA terminals
Fault Resistance (Ω)	1m, 100m, 1, 100, 1K, 10K

Evaluation Metrics

1. Maximum ground fault current and the current through the grounding network- Minimize these currents.
2. Voltage to ground throughout the magnet string - Maintain the voltage to ground within the existing HiPOT limits at cold temperature:
   - •Dipole Ring: ≤ 800 V
   - •Quad Ring: ≤ 450 V

Power Supply Grounding -Existing



During normal operation

- Ramp up , down and steady state- – Ground current (I_{PS_GND}) is sensed by measuring current through $R_{PS_GND_SEN}$

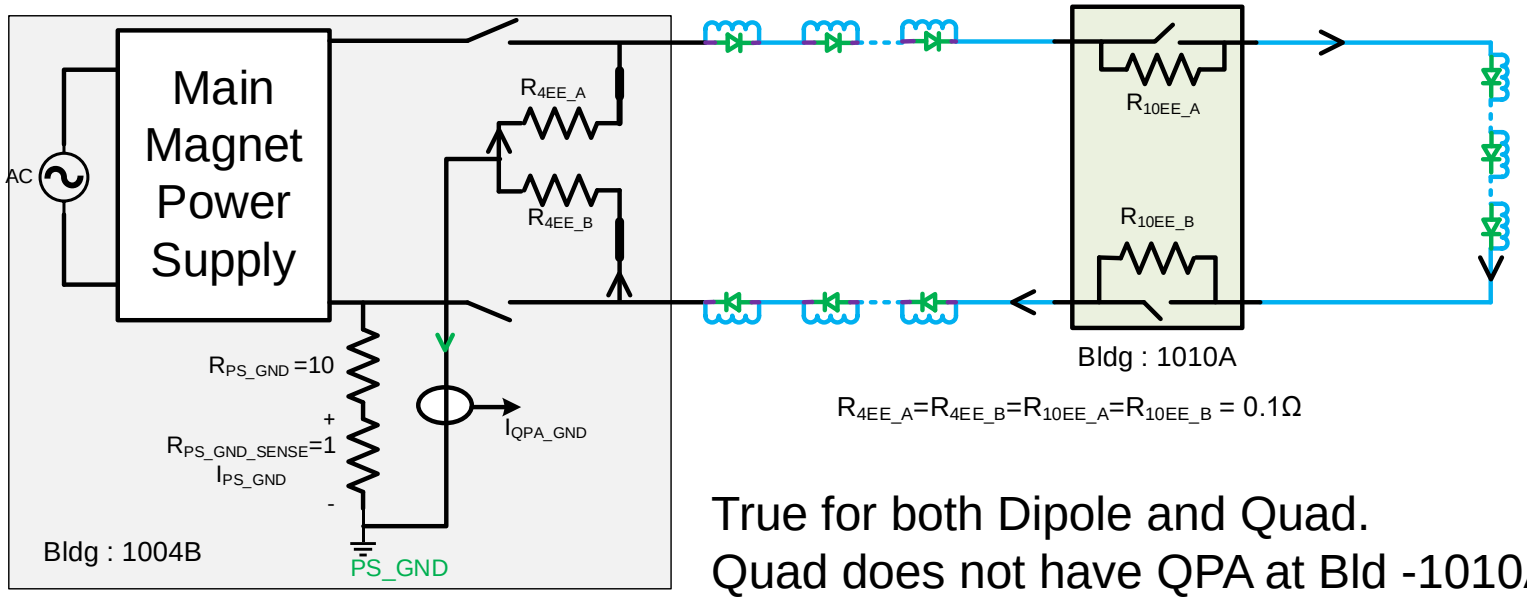
During Ground Fault

- Warning : ± 50mA for more than 1 second
- Trip : ± 500mA for more than 2 seconds

During Normal operation
Shut off , Quench discharge – Ground current (I_{QPA_GND}) is measured using current sensor

During Ground Fault

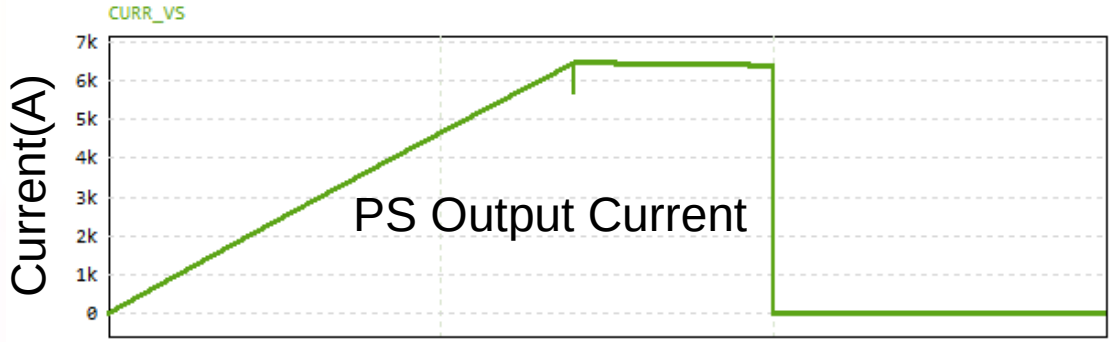
- Warning : ± 90mA for more than 1 second
- No Trip

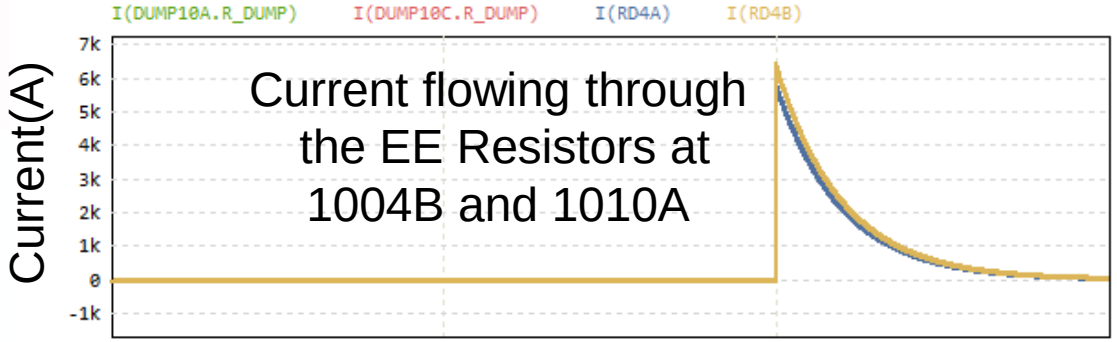


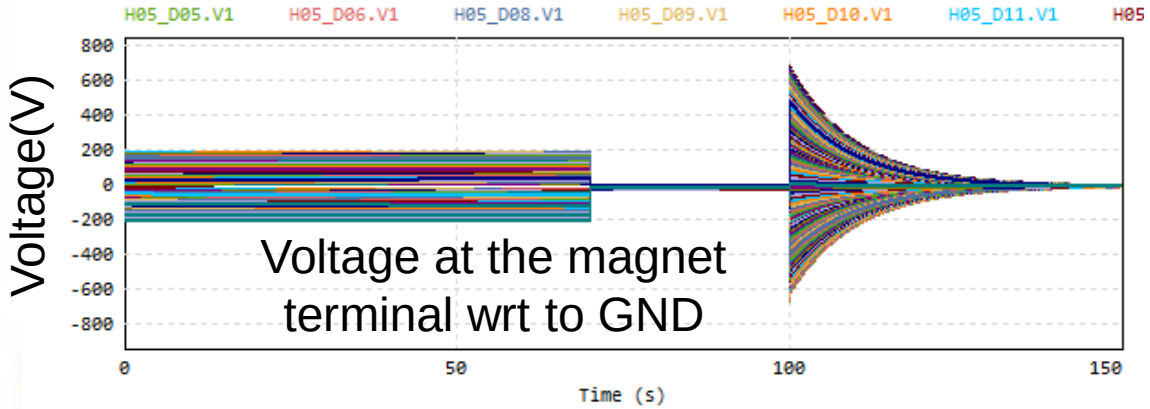
True for both Dipole and Quad.
Quad does not have QPA at Bld -1010A

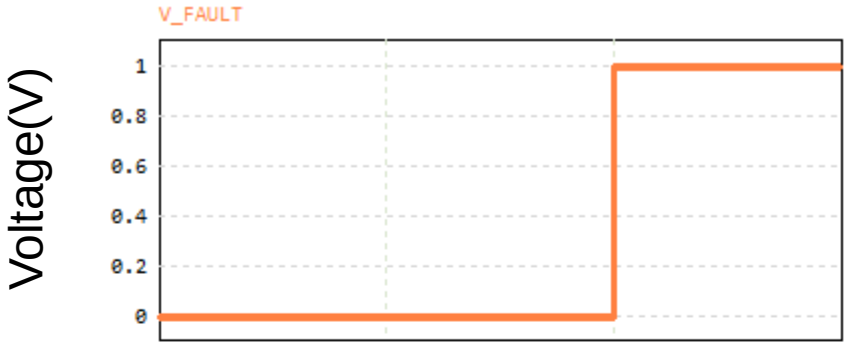
Simulation Output – Time Response

Ground Fault at 1010A
Ground Fault of 1ohm resistor
QPA – Solid Grounded

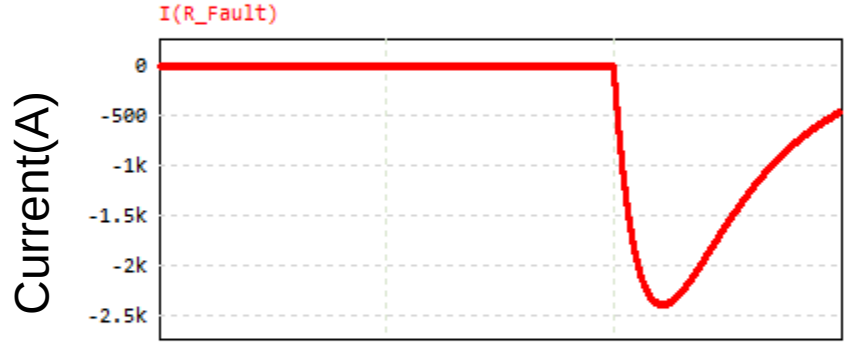




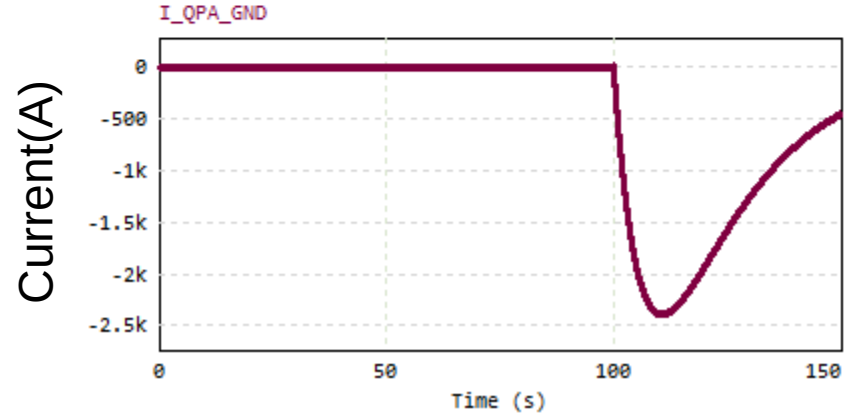




Fault Pulse



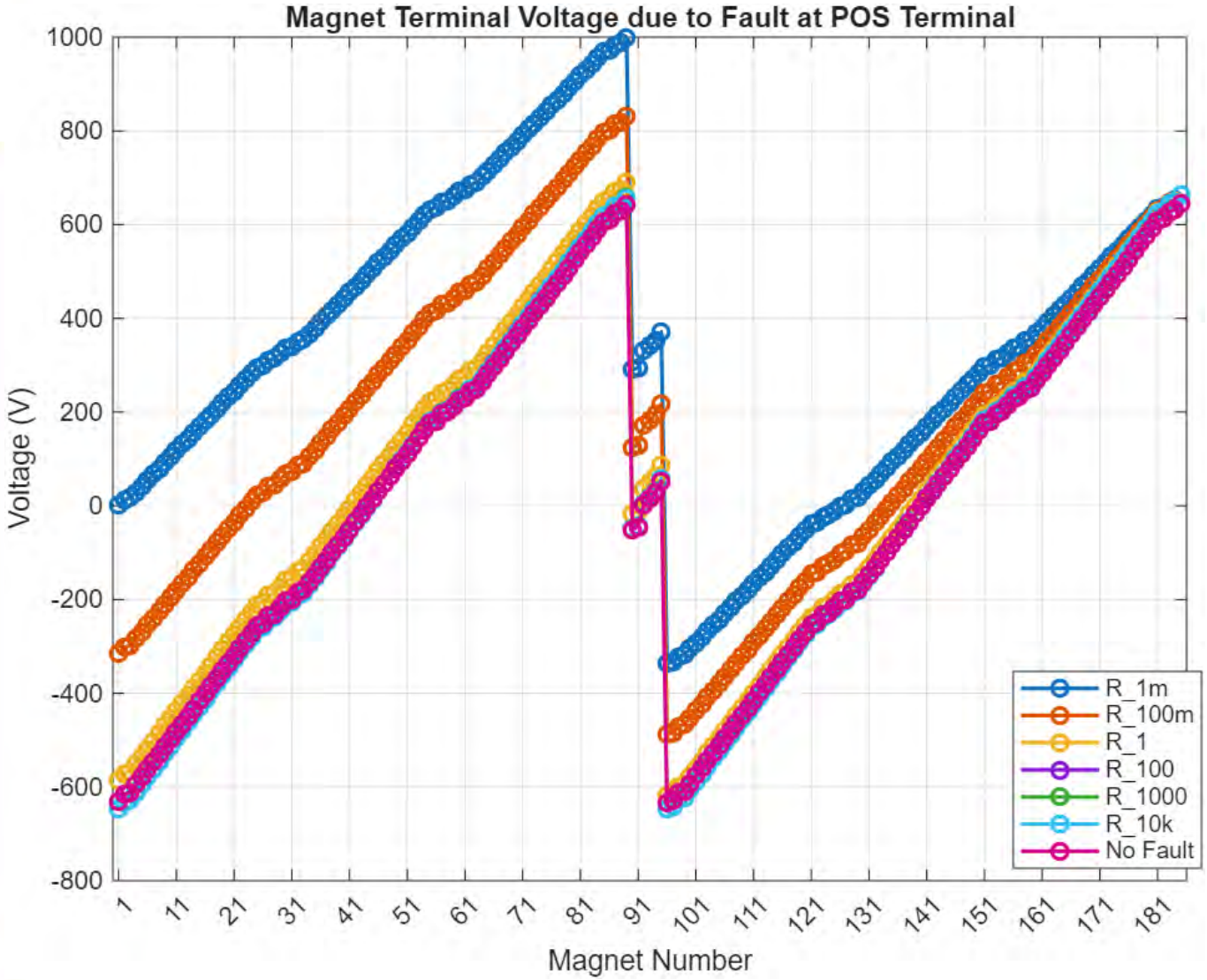
Current through the Fault Ground Resistor



Current through the QPA Ground

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Ground Fault at QPA Positive terminal- Solid Grounding

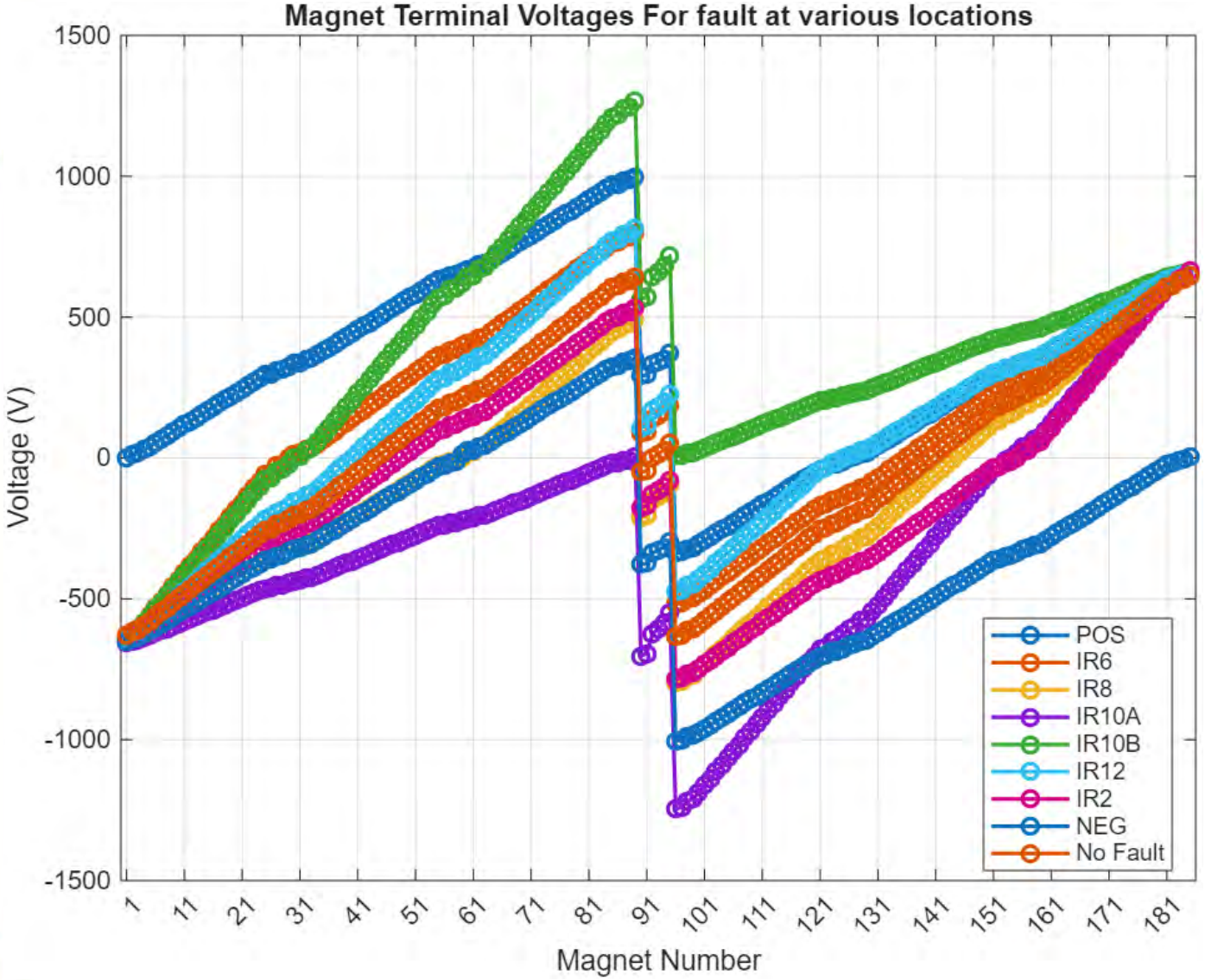


Fault Resistor (Ohms)	Peak Voltage (V)	Max I_{QPA_GND} (A)	Max I_{R_Fault} (A)
1m	997.69	6344.54	6344.54
100m	831.40	3252.66	3252.66
1	689.05	598.54	598.54
100	662.57	6.59	6.59
1000	662.57	0.66	0.66
10k	662.57	0.07	0.07

- Maximum ground-fault current occurs at minimum fault resistance.
- The resulting magnet terminal voltage is also highest.
- The voltage across the fault resistance approaches zero for a solid fault.

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Impact of Ground Fault Location on Ring Terminal Voltage Solid Grounding



Fault Resistor = 1mOhm
QPA Ground Resistor = 1mohms

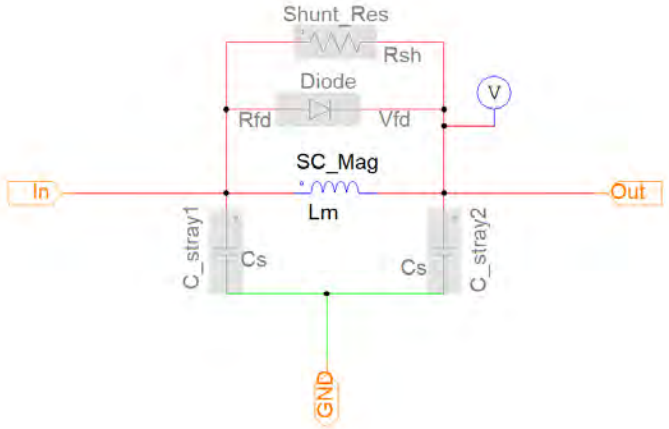
Fault Resistor (Ohms)	Max I_{QPA_GND} (A)	Peak Voltage (V)
POS	6344.54	997.69
IR6	1186.44	809.03
IR8	903.62	807.63
IR10A	2381.05	1255.13
IR10B	2396.41	1275.29
IR12	931.11	824.55
IR2	1169.32	1074.09
NEG	6883.41	1074.09

IR10A and IR10B faults produce the highest terminal voltages (~1.25 kV), while faults near the power supplies mainly increase the grounding current.

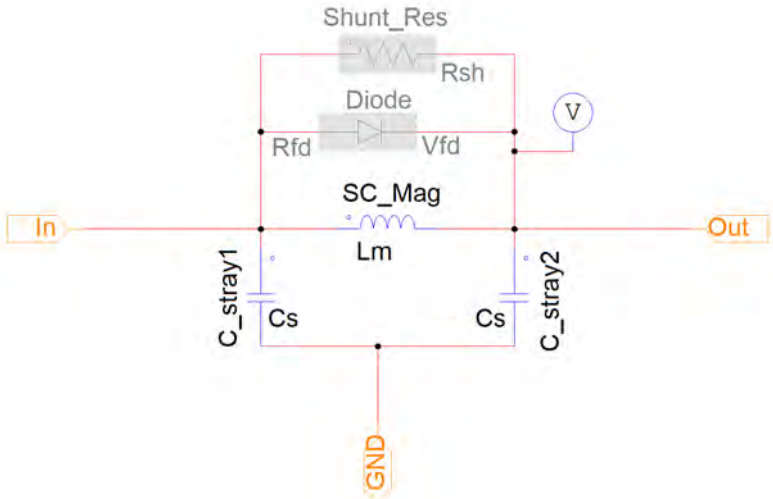
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Terminal Voltage Sensitivity to Magnet Stray Capacitance

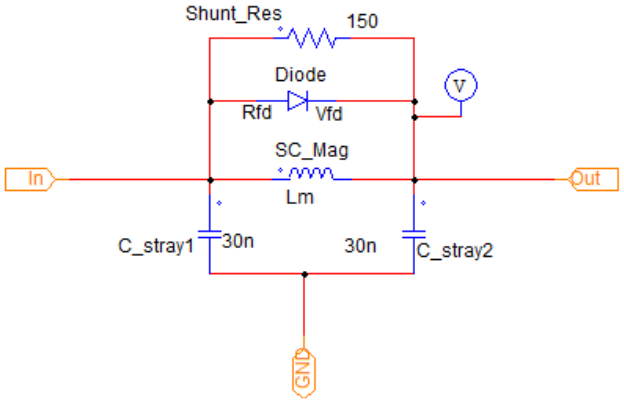
Magnet Equivalent Circuit



Simple Model
Only L



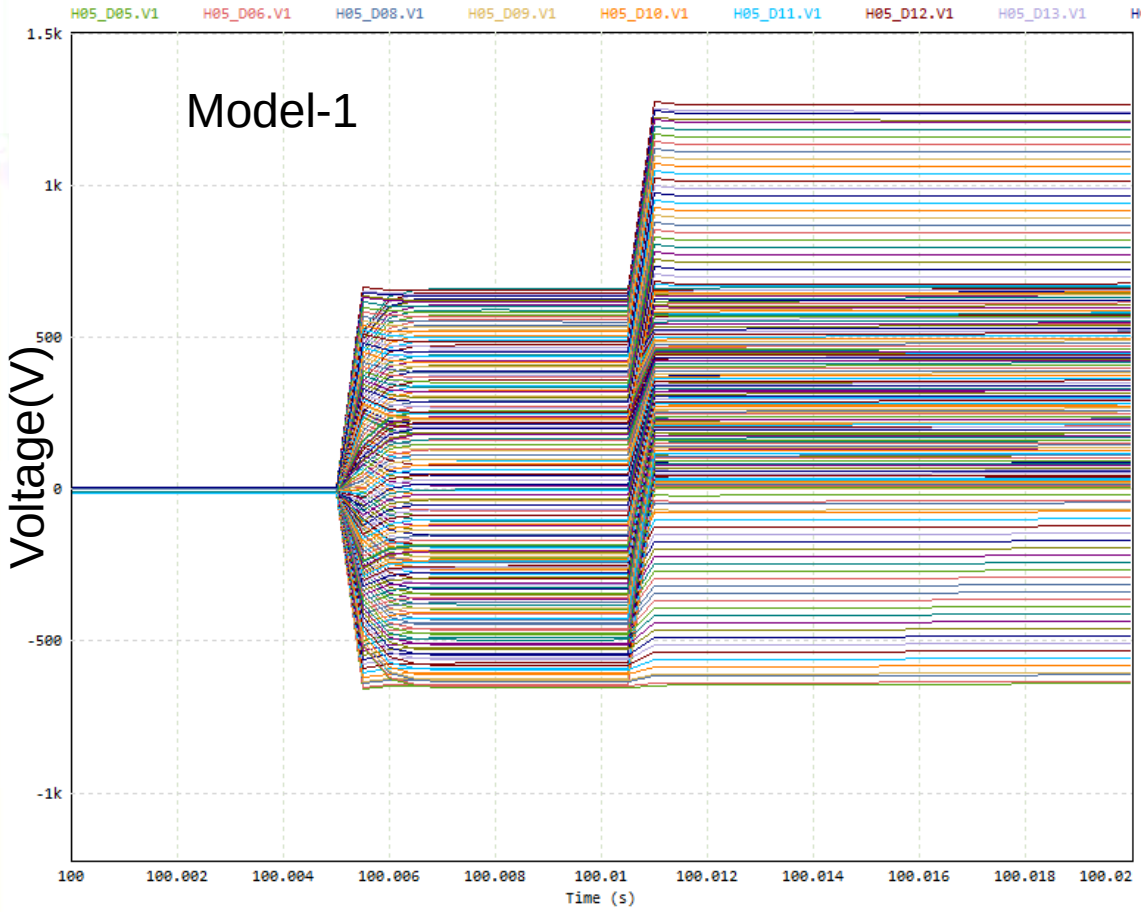
Model-2
L & Stray Capacitance
C_s=1nF



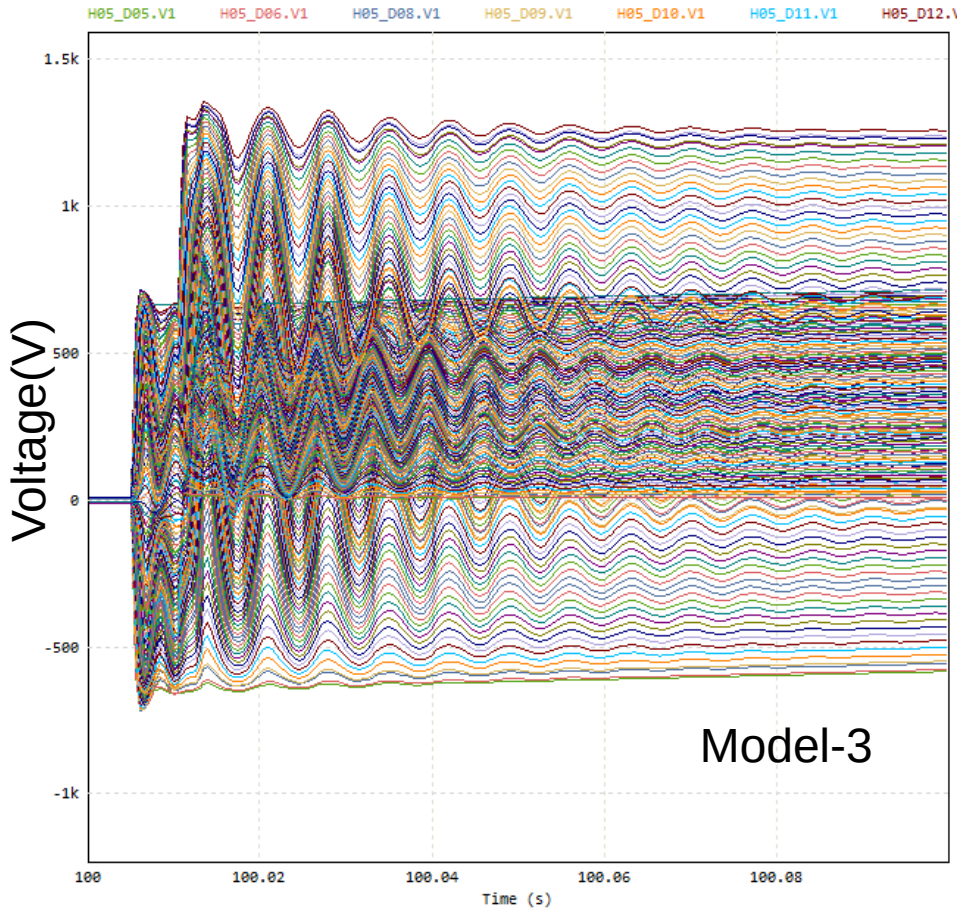
Model-3
L , Stray Capacitance & Shunt Resistance

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Effect of Magnet stray capacitance on the terminal voltage waveforms



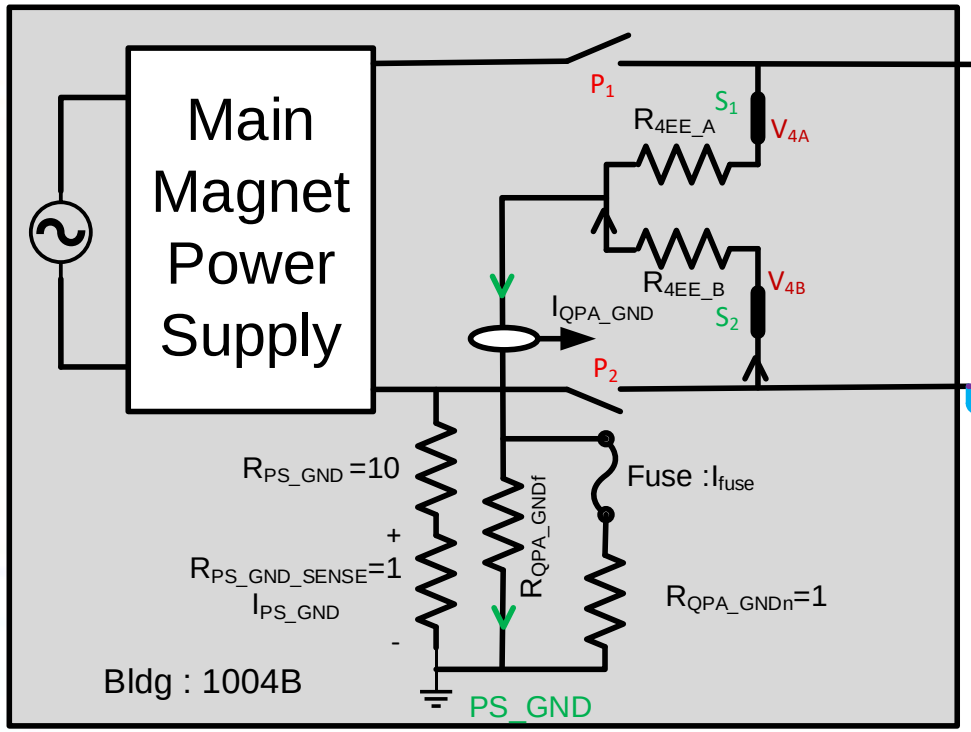
Fault at 1010B , QPA Ground : Solid
Fault Resistance : 1 ohm



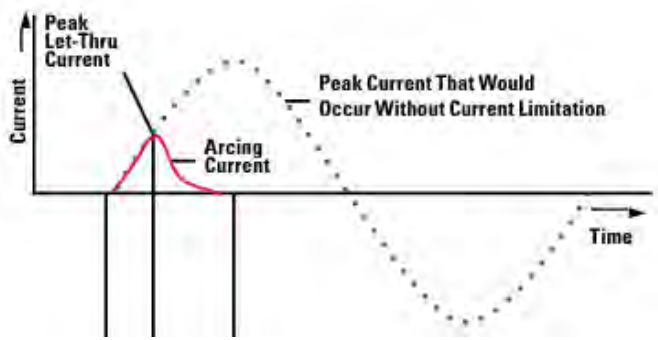
- The magnet stray capacitance introduces transient oscillations at QPA turn-on and during a ground fault.
- Its interaction with the circuit inductance produces an LC response, resulting in a slight increase in the peak magnet-to-ground fault voltage.

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Analysis - Grounding Scheme-1



- Very low resistance ground is required during normal operation- Prevent floating circuits common mode voltage from moving substantially in response to small leakage and capacitive current
- Behaves – Solid Grounding until Fuse blows



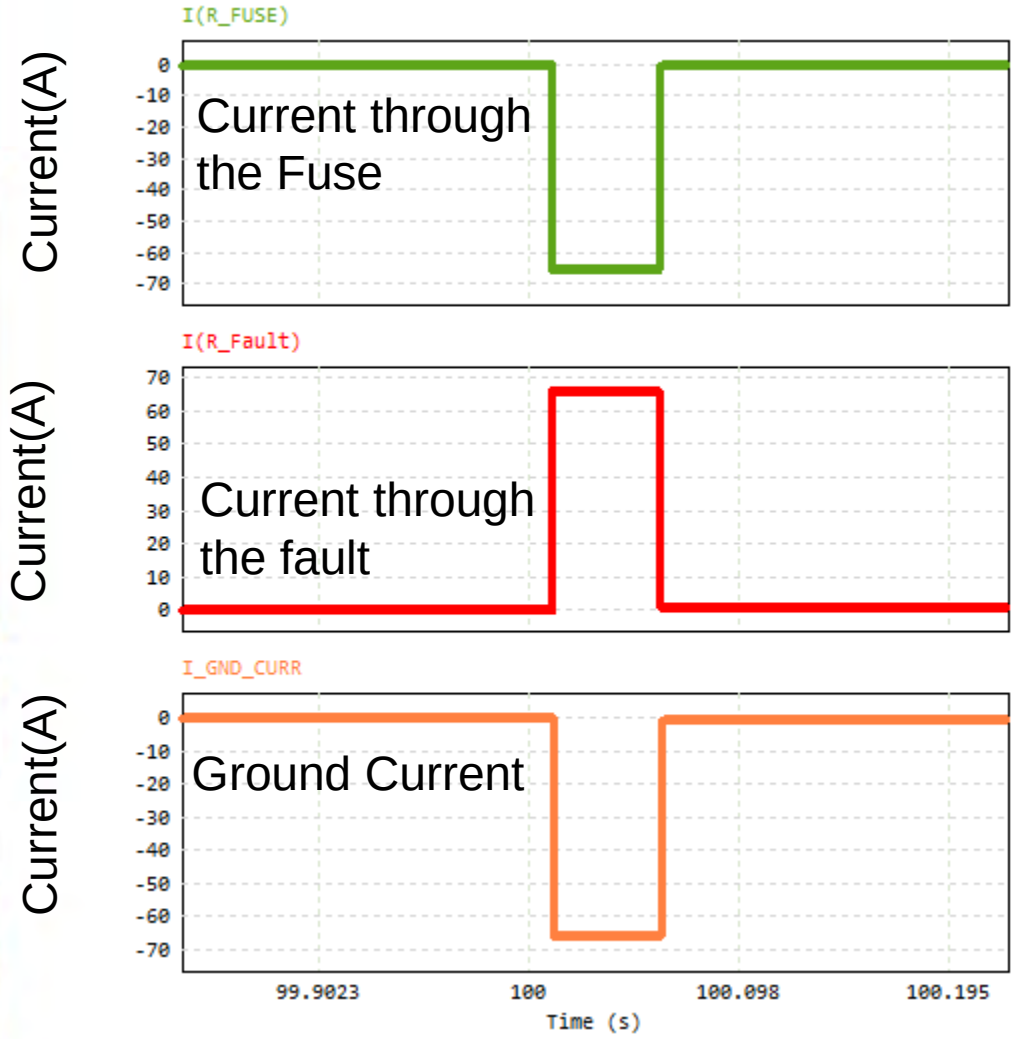
Ref: Littlefuse Fuseology Design guide , Overcurrent protection fundamentals

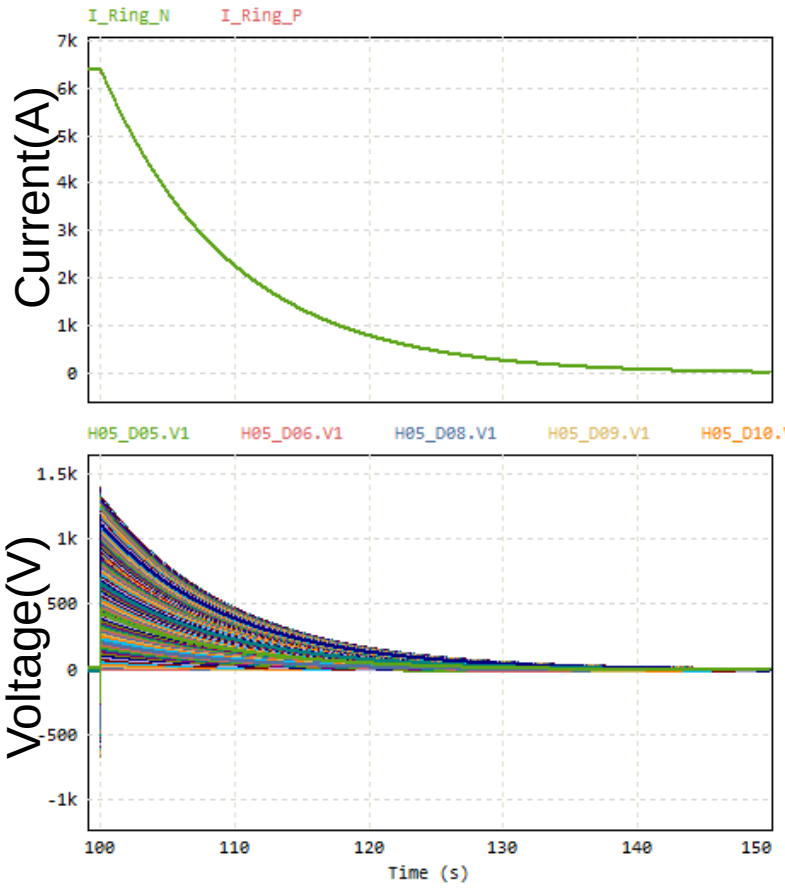
- **Melting time** → fuse element heats until it melts
- **Arcing time** → an arc exists after the element melts while the fuse interrupts current
- **Total clearing time** → melting time + arcing time

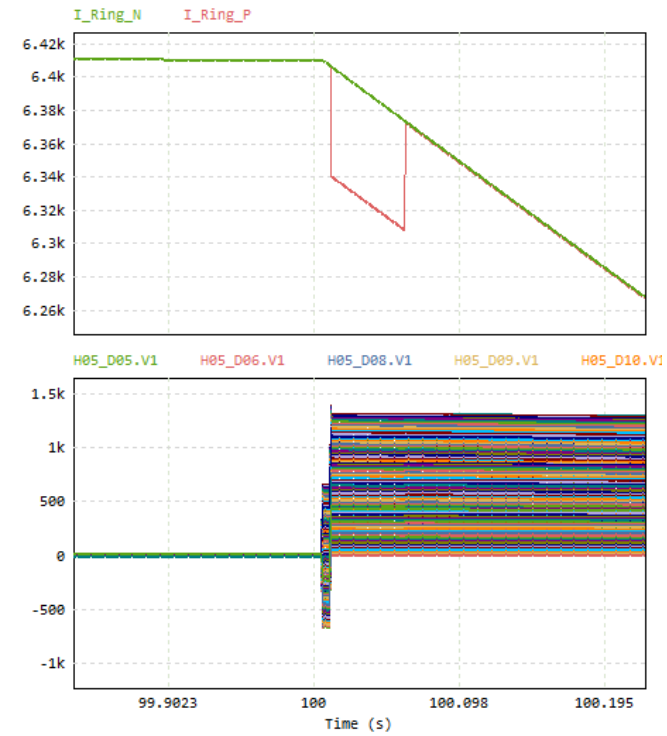
$$I^2t_{\text{clearing}} = I^2t_{\text{melting}} + I^2t_{\text{arcing}}$$

- As the fault currents are very high , I^2t of the fuse is considered as $50A^2.s$

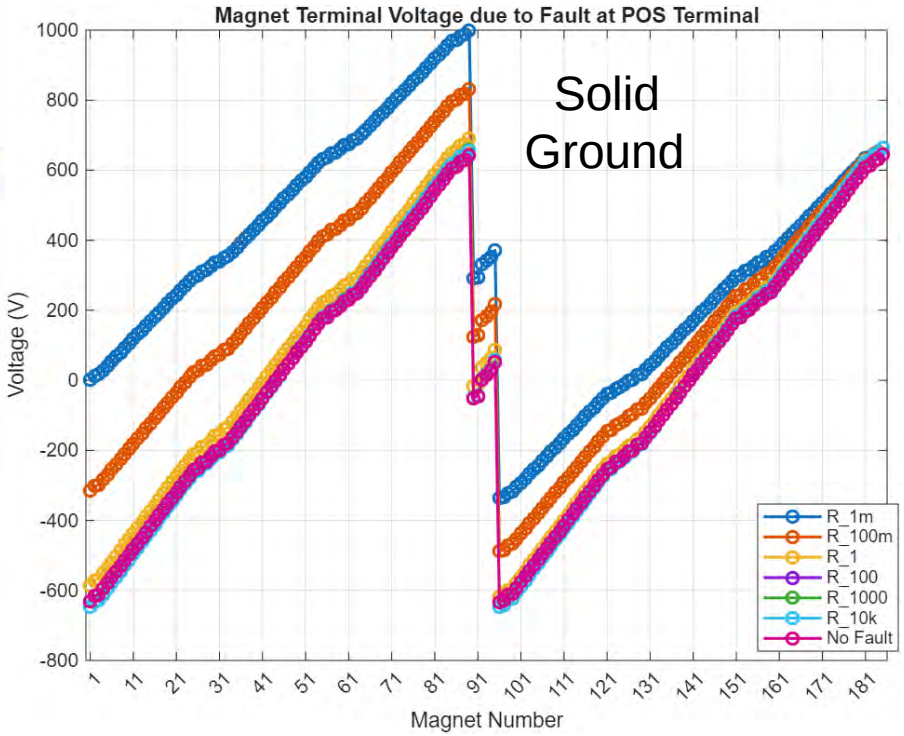
Simulation Results







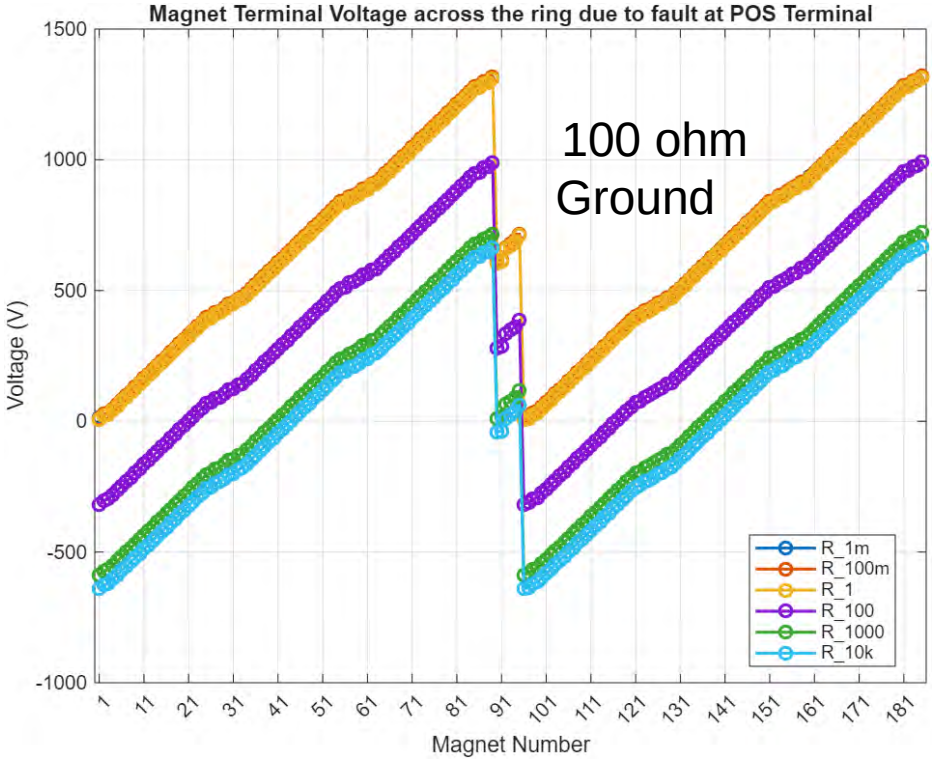
Effect of QPA Ground Resistance on Ground Fault at POS Terminal



Fault Resistor (Ohms)	Peak Voltage (V)	Max I_{QPA_GND} (A)	Max I_{R_Fault} (A)
1m	997.69	6344.54	6344.54
100m	831.40	3252.66	3252.66
1	689.05	598.54	598.54
100	662.57	6.59	6.59
1000	662.57	0.66	0.66
10k	662.57	0.07	0.07

Increasing the QPA ground resistance R_{QPA_GND} :

- Decreases ground-fault current, because the resistance in the fault-current path increases.
- Increases the magnet terminal voltage with respect to ground, because a larger portion of the circuit voltage appears across the grounding resistance, shifting the magnet potential relative to ground.



Fault Resistor (Ohms)	Peak Voltage (V)	Max I_{QPA_GND} (A)	Max I_{R_Fault} (A)
1m	1321.86	6.59	6.59
100m	1321.21	6.59	6.59
1	1315.34	6.53	6.53
100	992.38	3.30	3.30
1000	722.56	0.60	0.60
10k	669.11	0.07	0.07

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Ground Fault- QPA Ground Resistance Comparison

Fault Resistance of 1mohm								
QPA Ground Resistor (Ohms)	1m (Solid)		1ohm		10 ohm		100 Ohm	
Location	Vmax (V)	I_{QPA_GND} (A)	Vmax (V)	I_{QPA_GND} (A)	Vmax (V)	I_{QPA_GND} (A)	Vmax (V)	I_{QPA_GND} (A)
POS	997.69	6344.54	1287.10	597.93	1315.79	65.32	1321.86	6.59
IR6	796.15	0.60	807.77	0.60	862.69	0.59	883.39	0.52
IR8	796.89	0.36	797.01	0.36	836.71	0.35	862.39	0.32
IR10A	1246.41	0.95	1246.50	0.95	1266.15	0.94	1300.00	0.88
IR10B	1275.29	2396.41	1266.51	0.95	1281.53	0.95	1313.80	0.89
IR12	813.40	0.37	813.53	0.37	852.90	0.36	878.85	0.33
IR02	784.98	0.59	795.74	0.59	849.20	0.58	869.52	0.52
NEG	1004.45	6325.13	1279.68	600.10	1320.82	65.57	1323.79	6.62

Summary

- EIC Hadron Storage Ring
  - o High-current superconducting magnet systems with significant stored energy — 5.76 kA / 69.7 MJ for the dipole ring.
- Precision Power Conversion
  - o Accelerator beam control requires precise and reproducible magnet current.
  - o Precision current regulation + DCCT feedback enables ppm-level current performance; both BTP and COTS-based architectures are applicable.
- Quench Protection
  - o Quench protection requires coordinated detection, current bypass, energy extraction, and power-supply shutdown.
  - o Coupled electrothermal modeling evaluates the key design trade-off: $T_{hotspot}$ Vs V_{peak}
- System Protection & Grounding
  - o A floating magnet circuit requires a controlled ground reference for voltage-to-ground management and ground-fault detection.
  - o Grounding design involves a fundamental trade-off: R_{gnd} ↑ = I_{fault} ↓ , V_{mag_ground} ↑

Reliable superconducting-magnet operation requires precision current control during normal operation and coordinated energy, quench, and fault management during abnormal operation

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