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imagination at work

Quench Protection of Multi-coil LTS Magnets

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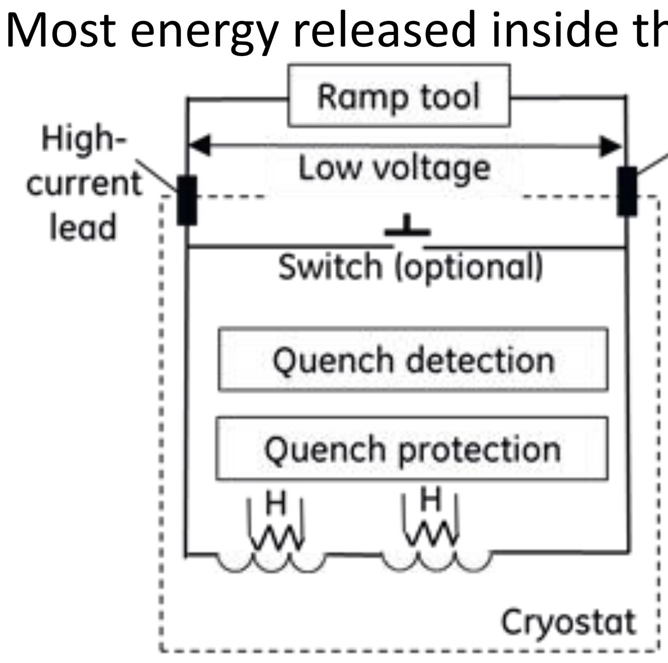
Summary

A new quench protection approach for LTS magnets minimizes the number of components that must be activated during quench. Electrically and inductively coupled coils are electrically connected in a number of possible ways: all in parallel; several parallel-connected groups, with each group consisting of several series connected coils; several series-connected groups, with each group consisting of several coils in parallel. If one of the parallel-connected coils or groups quenches, current in this coil or group decreases while current in the other parallel-connected coils or groups tries to increase to keep total current flow in the circuit the same. Quench is limited to only the quenched coil or group. In some cases, the equipment may continue operation after quench, although at a somewhat reduced capacity. The approach is advantageous for superconducting systems that consist of many similar coils with relatively weak inductive coupling such as motors or generators.

Introduction - Existing quench protection approaches

Internal protection

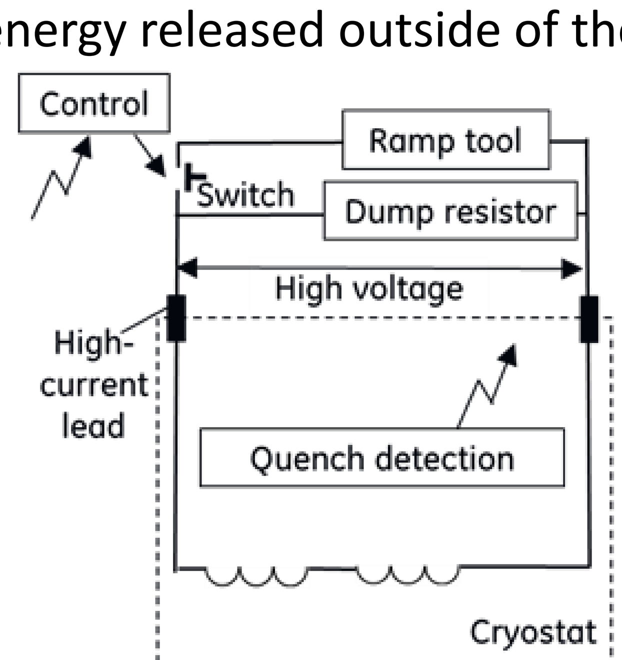
Most energy released inside the cryostat



- Used in MRI, NMR, accelerator magnets
- Magnets often operate in persistent mode
- All or most coils must become resistive
- **Con:** magnet out of operation for several days after quench: refill, re-cool, re-ramp

External protection

Most energy released outside of the cryostat.



- Used: power apps., HEP, 11.7 T Iseult MRI
- Require high voltage across the leads, fast external switch (if operate in persistent mode)
- **Con:** Reliability: detection, high voltage

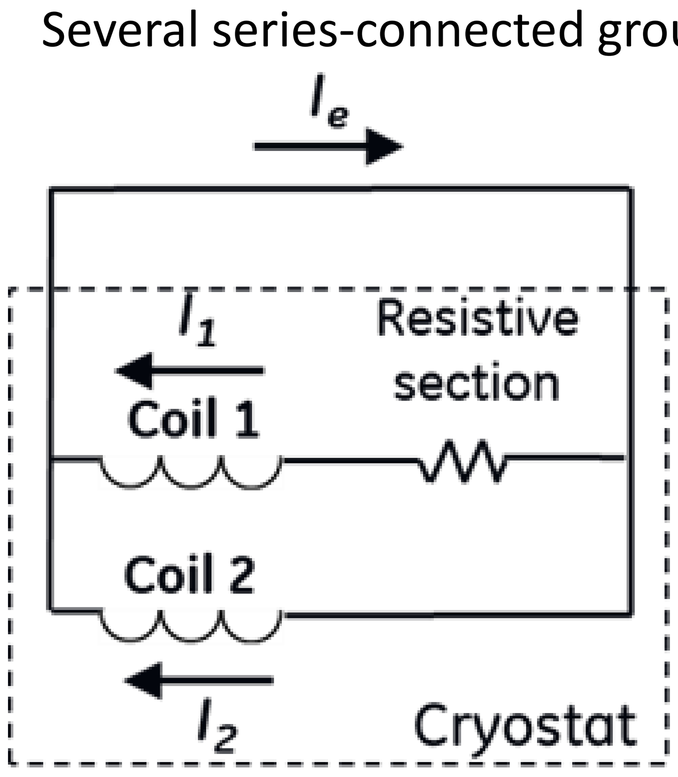
Quench protection of multi-coil magnets – principle of operation

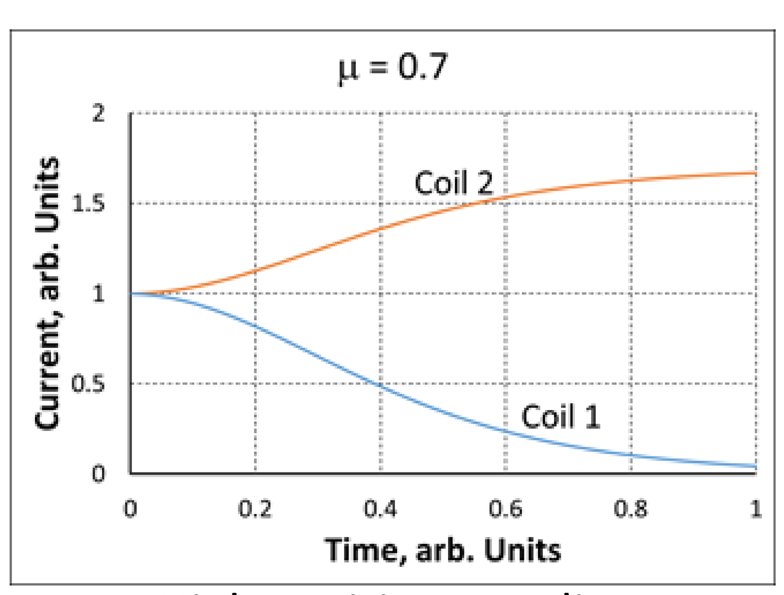
Objective: Continue operation if one coil quenches, minimize components involved

Design approach: Quench of one coil does not require the magnet quench

Configurations:

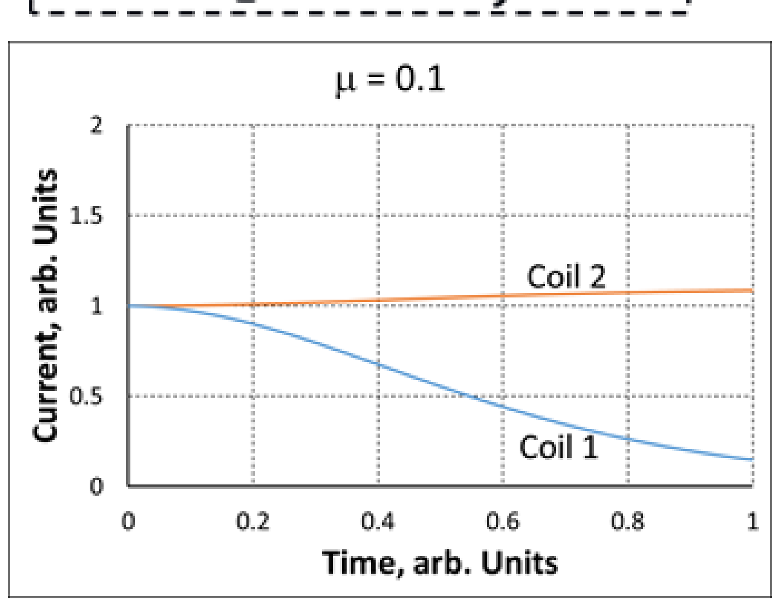
1. Parallel connection of the coils
2. Several parallel-connected groups. Each group: array of series connected coils
3. Several series-connected groups. Each group: a number of parallel-connected coils





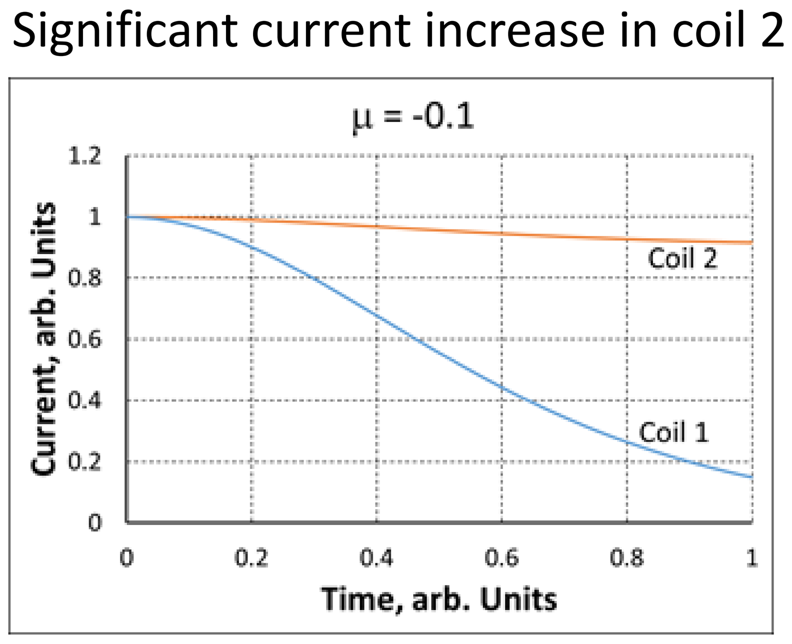
High positive coupling

Significant current increase in coil 2



Low positive coupling

Coupling μ = ***M/L***



Negative coupling

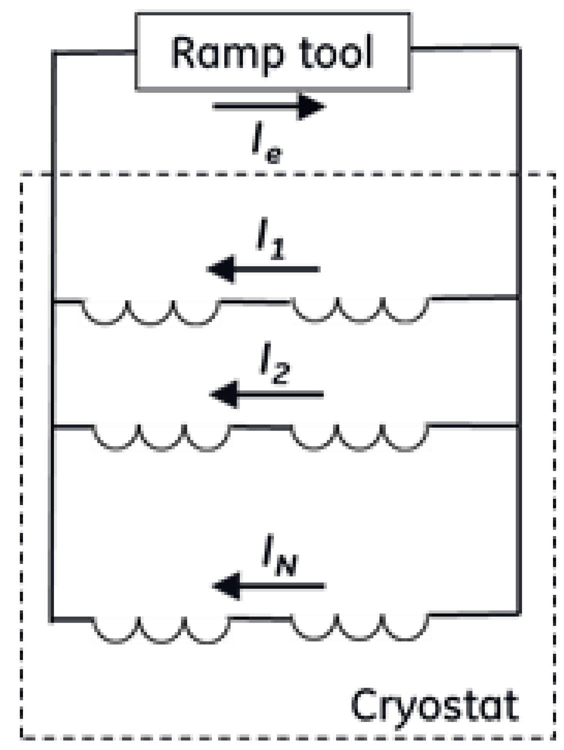
Slow current decay in coil 1

Magnet continues operation – without quench protection activation - if:

1. Coil 1 can absorb energy E_ox(0.5 – $M/2L$) without damage (E_o – magnet energy), and
2. Coil 2 does not quench at current I_ox(1 + M/L)

After recovery and fast cool down, coil 1 restores operation

Multi-coil groups



$I_k = \frac{I_e}{L_{eff}} \sum_{n=1}^{N} l_{kn}$ - Current in coils after ramp

$I_n = \frac{I_e}{L_{eff}} \left(\sum_{i=1}^{N} l_{in} - \frac{l_{nj}}{l_{jj}} \sum_{i=1}^{N} l_{ij}\right)$ Current in coil ***n*** after quench

$L_{eff} = \left(\sum_{n,j=1}^{N} l_{nj}\right)^{-1}$ - Magnet inductance; l_{nj} are elements of reverse-the inductance matrix

Approach works best if:

- Large number of coils (>10)
- All coils are about the same size. Otherwise, smaller coils will be overloaded
- Weak inductive coupling, either positive or negative
- Examples: motors, generators, FCL, multi-strand cables, etc.

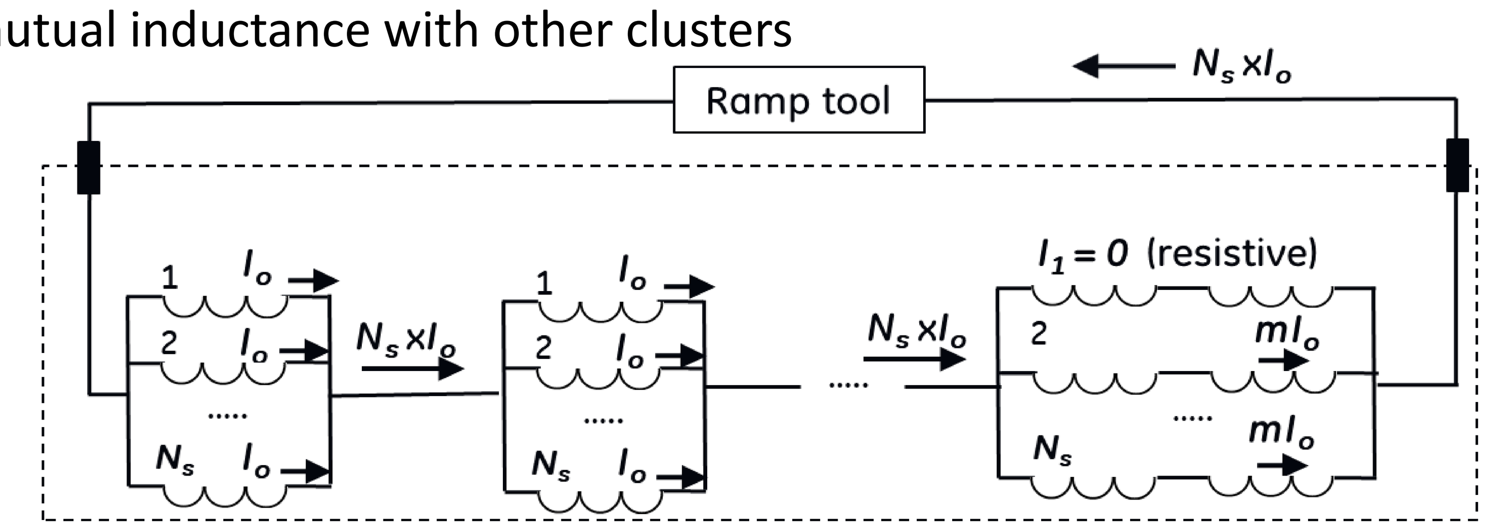
Challenges and solutions

Parallel connection of the superconducting components requires high current charging leads ~10 kAmp. Issues:

- Persistent joints, switch, ramp losses
- Equalization of currents in the branches

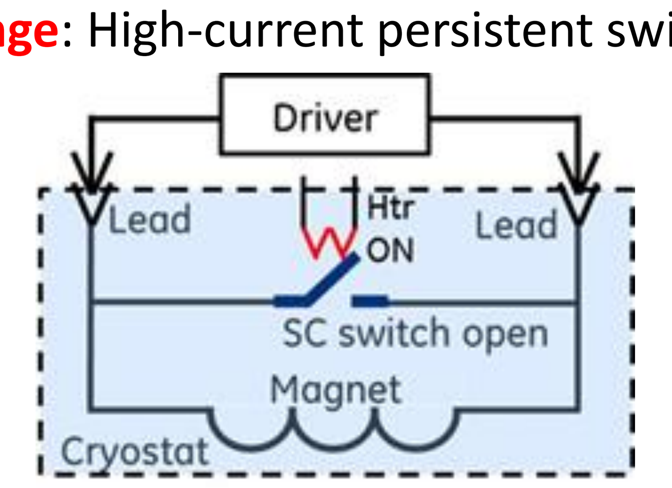
Configuration 1 - Combine several parallel-connected components in series

- Reduced input current
- All parallel-connected clusters continue operation even when one coil quenches
- Preferred configuration: clusters are magnetically-equal including self- and mutual inductance with other clusters

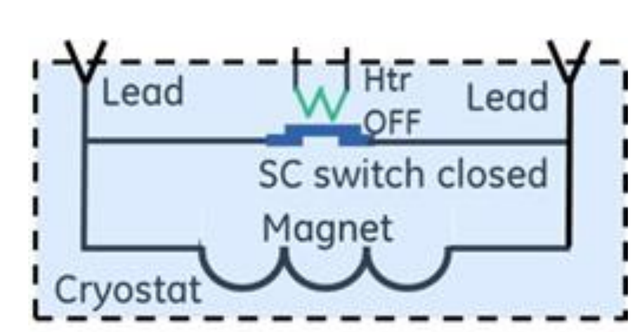


Configuration 2 - System operation in persistent mode

- Common MRI/NMR approach
- Low operation losses: zero current in the leads after ramp
- **Challenge**: High-current persistent switch

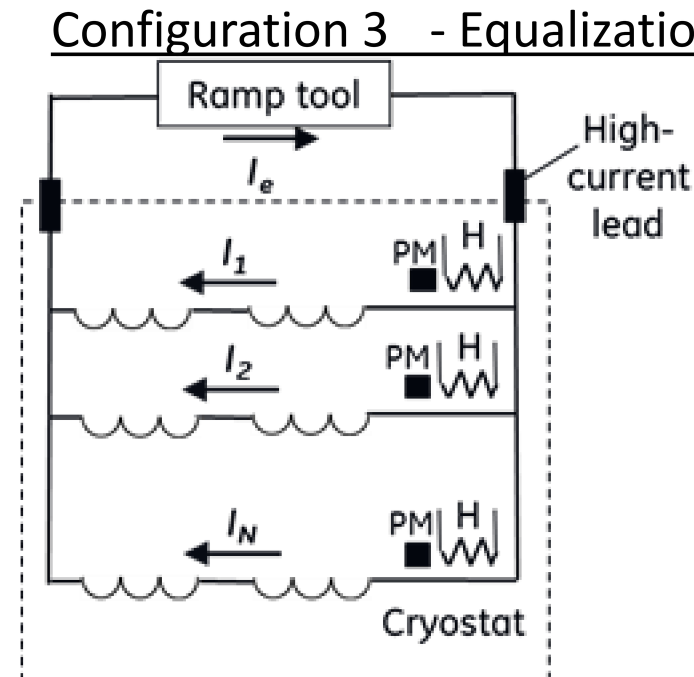


Ramp mode



Persistent operation

Configuration 3 - Equalization of current in parallel branches



- Use heaters only at the end of ramp: minimize losses
- Permanent magnets (PM) increase magnetic field on conductor, reduce need in heaters
- Ramp up after all currents are equal (zero)

Conclusion

A multi-coil, multi-branch configuration of superconducting coils may not require a complete ramp down of the magnet system to zero field. The system may continue operation with a loss of only a relatively small part of stored energy or magnetic field, albeit at reduced performance parameters. The system may require fewer, more reliable components.