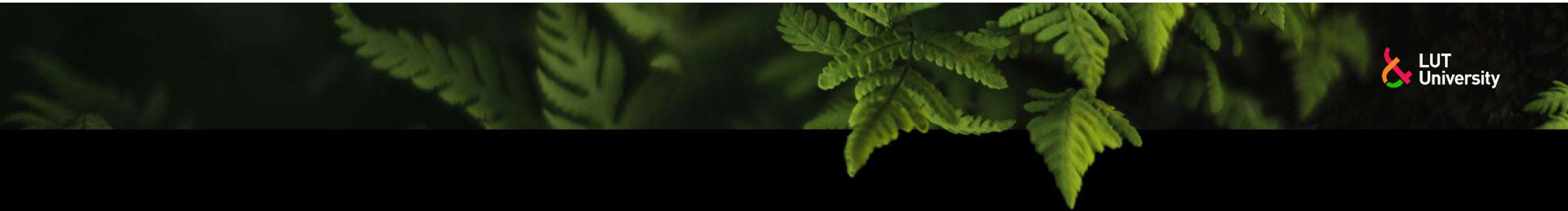

Doctoral course on High-Specific Power Electrical Motors and Drives 04/05/2022

THERMAL DESIGN

Thermal Network Model

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OVERVIEW

- Thermal-Electrical Analogy
- Thermal Resistance
- Thermal Capacitance
- Losses in Electrical Machines
- Cooling Systems
- Thermal Network Model
- Steady State analysis
- Transient analysis
- Duty cycle (or driving cycle) analysis

THERMAL-ELECTRICAL ANALOGY

The analogy between the thermal and electrical models can be fully understood in thermal conduction.

Heat conduction in solids is quite similar (there are some limitations due to non-linearities in the relationship between voltage and current at extremely high and low values) to the conduction of the electricity in electrical conduction.

If a differential of potential exists between two points A and B, there will be a current flow from A to B, which is limited by the resistance that the electrons encounter in this path.

In the thermal conduction, heat is transported by the vibration of the molecules from point A to B if exists a temperature difference between these two points.

THERMAL-ELECTRICAL ANALOGY

Heat conduction is governed by Fourier's law, which can be summarized by:

$$Q = k\,S\,\frac{T_A - T_B}{\delta}$$

Where Q is the heat flow rate, k is the coefficient of thermal, conductivity S is the normal area to the direction of heat, and δ is the distance between the point A and B.

Electric current flow is governed by Ohm's law, which can be summarized by:

$$I = \frac{V_A - V_B}{R_e}$$

THERMAL-ELECTRICAL ANALOGY- RESISTANCE

$$I = \frac{\Delta V}{R_e} = \frac{V_1 - V_2}{R_e} \qquad Q_{cond} = kS\frac{\Delta T}{\delta} = \frac{T_1 - T_2}{R_{t,cond}}$$

$$R_e = \frac{\delta}{\sigma_e S} \qquad R_{t,cond} = \frac{\delta}{kS}$$

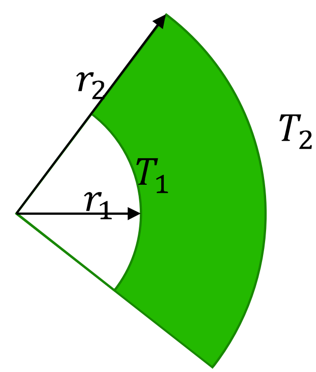
The temperature can be associated with the electrical potential, the current to the heat flow, and the electrical resistance to the thermal one. If the conduction is considered for the thermal exchange, also the expression of the thermal resistance and the electrical one can be associated.

σ_e (electrical conductivity) $\rightarrow$ k (thermal conductivity)

THERMAL-ELECTRICAL ANALOGY- RESISTANCE

Considering a cylindrical wall, the thermal resistance can be computed according to:

$$R_{t,cond} = \frac{\ln(r_2/r_1)}{2\pi k L}$$



CONVECTIVE HEAT TRANSFER

The second method to exchange heat is convection. The convective heat transfer exists when an object has a higher o lower temperature than a surrounding fluid and never in a solid. The fluid could be a liquid or a gas. The equation of the convection heat transfer is Newton's Law of Cooling.

$$Q_{conv} = hS(T_{\infty} - T_s)$$

Where Q_{conv} is the convective heat transfer rate, h is the convective heat transfer coefficient, S is the surface area in the fluid, T_{∞} is the bulk temperature of the surrounding fluid, and T_s is the surface temperature of the object.

CONVECTIVE HEAT TRANSFER COEFFICIENT

The main problem in the convection heat exchange is the computation of the convective heat transfer coefficient (h), which depends on many factors both for the fluid's physical properties and the physical situation. The coefficient **is not** a property of the fluid, and it can be determined **experimentally** or with **CFD** analyses. The parameters depend on the roughness and the **geometry** of the surface, the nature of **fluid motion** (natural or forced convection), the **property** of the fluid (viscosity, density), and the bulk fluid **velocity**.

THERMAL-ELECTRICAL ANALOGY RESISTANCE

$$I = \frac{\Delta V}{R_e} = \frac{V_1 - V_2}{R_e}$$

$$R_e = \frac{\delta}{\sigma_e S}$$

$$Q_{conv} = hS\Delta T = hS(T_1 - T_2)$$

$$R_{t,conv} = \frac{1}{hS}$$

Also for the convection, it is possible to define an equivalent thermal resistance for the thermal network model.

RADIATION HEAT TRANSFER

The last method to exchange heat is radiation. The radiation heat transfer also exists in the absence of matter and occurs without any medium at all. The heat goes from a hotter region to a colder one. The equation of the radiation heat transfer is Stefan-Boltzmann's Law.

$$Q_{rad} = \varepsilon\sigma S(T_p^4 - T_s^4)$$

Where Q_{rad} is the radiation heat transfer rate,ε is the emissivity of the surface, σ is the Stefan-Boltzmann constant, S is the surface area viewed by the body s of body p, T_p is temperature of body p, and T_s is the temperature of body s.

RADIATION HEAT TRANSFER COEFFICIENT

The main problem in the radiation heat exchange is the computation of the area factor S, the surface area viewed by the body s of body p. This coefficient depends on the distance, the shape, and the angle between the surfaces of the two bodies. Using some math manipulation it is possible to modify the expression in:

$$Q_{rad} = \varepsilon \sigma S\left(T_p^2 + T_s^2\right)\left(T_p + T_s\right)\left(T_p - T_s\right)$$

$$Q_{rad} = h_r S\left(T_p - T_s\right)$$

$$h_r = \varepsilon \sigma \left(T_p^2 + T_s^2\right)\left(T_p + T_s\right)$$

THERMAL-ELECTRICAL ANALOGY RESISTANCE

$$I = \frac{\Delta V}{R_e} = \frac{V_1 - V_2}{R_e}$$

$$R_e = \frac{\delta}{\sigma_e S}$$

$$Q_{rad} = h_r S \Delta T = h_r S (T_1 - T_2)$$

$$R_{t,rad} = \frac{1}{h_r S}$$

Also for the radiation, it is possible to define an equivalent thermal resistance for the thermal network model.

THERMAL-ELECTRICAL ANALOGY CAPACITANCE

The objects typically have a thermal capacitance (called thermal mass) which measures how much heat an object can store. The temperature in the objects does not change instantaneity, but it is required for a specific time so that the object can reach its final temperature. The parameter that indicates the speed of an object varies its temperature is the thermal capacitance linked to the following equation.

$$Q_c = mc_p \frac{d(T_1 - T_2)}{dt}$$

Where m is the mass of the object and c_p is the specific heat. From these two terms, it is possible to define the thermal capacitance:

$$C = mc_p$$

THERMAL-ELECTRICAL ANALOGY HEAT SOURCE

The heat source in the field of the electrical machines represents the losses of the machine. It is possible to add one heat source for each loss that we want to simulate. It is also possible to divide the losses into more elements when they are distributed in different areas of the machine (i.e., the core losses). The losses represent the heat produced by the machine, and it can be simulated in the thermal equivalent network as an ideal current generator connected to the point at which we want to simulate those losses.

The losses can be a function of the temperature as is the case with the Joule losses.

THERMAL-ELECTRICAL ANALOGY LOSSES

The losses that are typically simulated in the thermal equivalent network are:

- Joule Losses (in the winding, function of the temperature which modifies the phase resistance value). These losses are typically simulated with one heat source that acts in the motor's slot. Only one slot generally is simulated because, during the motor rotation, each slot has affected by the same value of current.
- Core Losses (in the stator and rotor core, only function of the electromagnetic aspects). These losses are typically simulated with two, three, or four heat sources. There is almost one heat source for the stator core losses and one for the rotor core losses (also in the presence of a Synchronous Machine due to the flux harmonics). For better results, it is possible to divide the losses into two heat sources, one for the teeth and one for the yoke.
- Magnet losses (in the permanent magnet if present) or Rotor Joule losses (in the winding or cage inside the rotor if present). They are a function of the temperature, which modifies the resistivity of the materials.

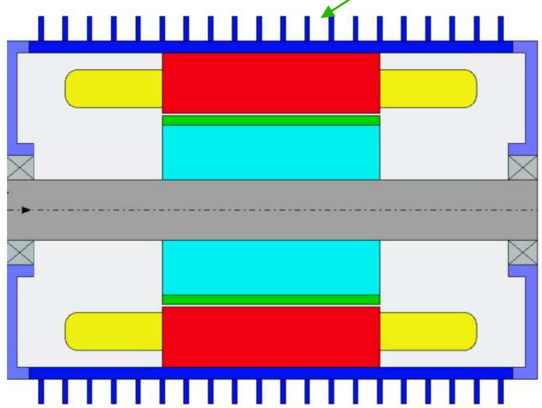
COOLING SYSTEMS

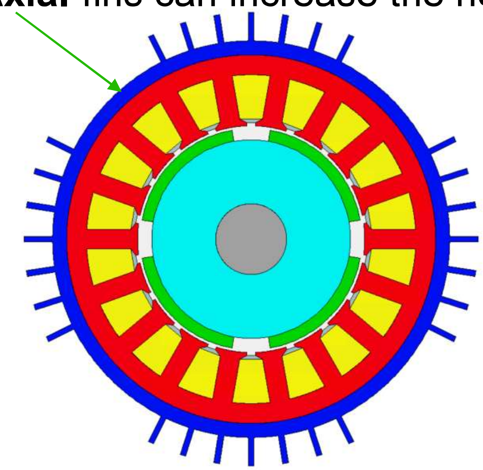
- Totally Enclosed Non-Ventilated
- Totally Enclosed Fan Cooled
- Through Ventilation
- Totally Enclosed with Internal Circulating Air
- Open End-Shield Cooling
- Water Jackets
- Submersible Cooling
- Wet Rotor & Rotor Water Jacket
- Spray Cooling
- Direct Conductor Cooling

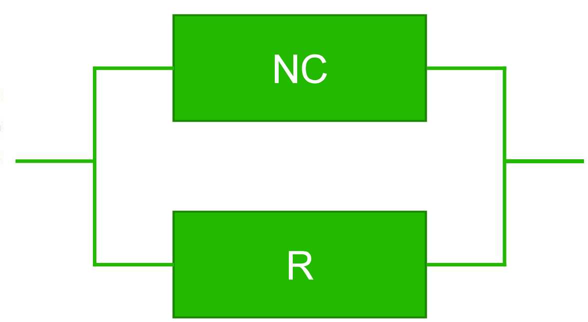
TOTALLY ENCLOSED NON-VENTILATED

The only heat exchange with the environment is the natural convection (NC) and the radiation (R). It is possible to simulate this with two resistance in parallel, one for each heat exchange.

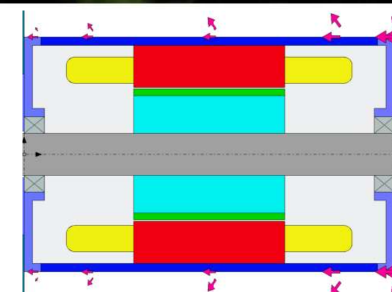
The parameters of the thermal resistances depend on the air properties and the shape of the housing. The adoption of **Radial** or **Axial** fins can increase the heat thermal coefficients.





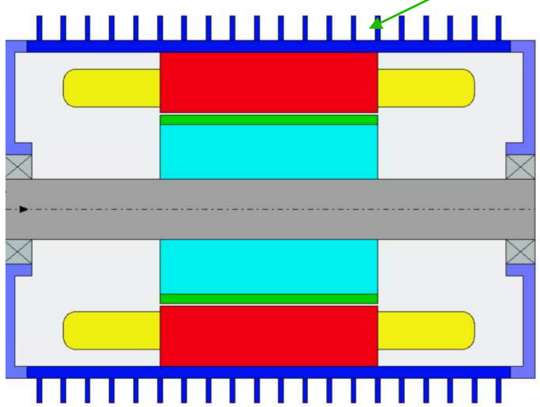


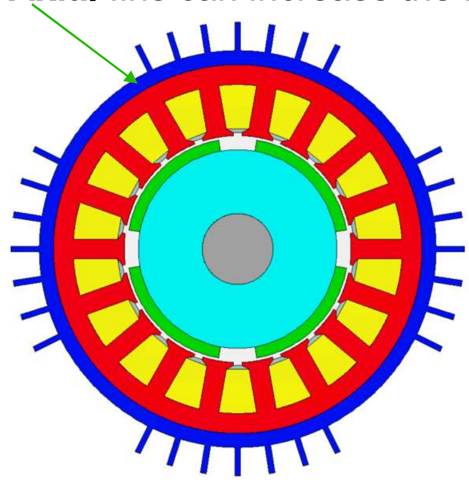
TOTALLY ENCLOSED FAN-COOLED

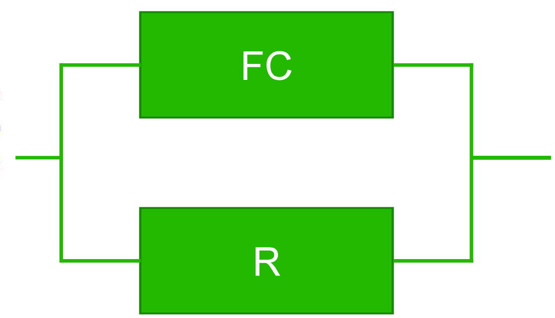


The heat exchange with the environment is the forced convection (FC) and the radiation (R). It is possible to simulate this with two resistance in parallel, one for each heat exchange.

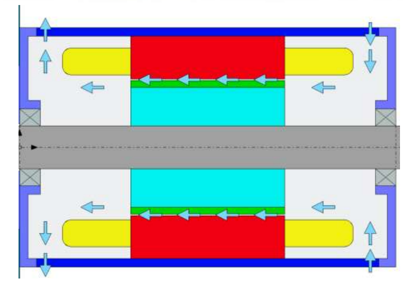
The parameters of the thermal resistances depend on the air properties, the speed of the fluid, and the shape of the housing. The adoption of **Radial** or **Axial** fins can increase the heat thermal coefficients.



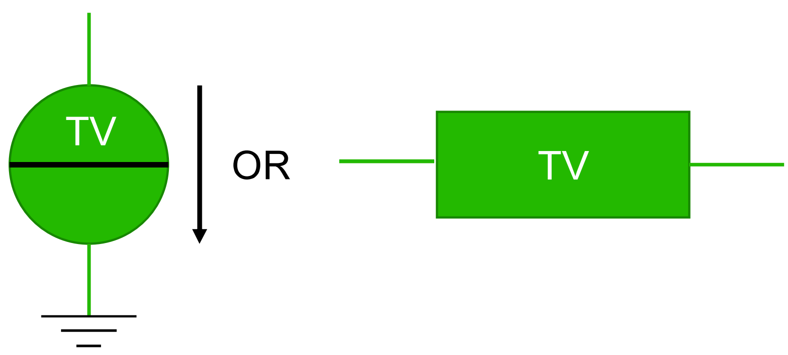


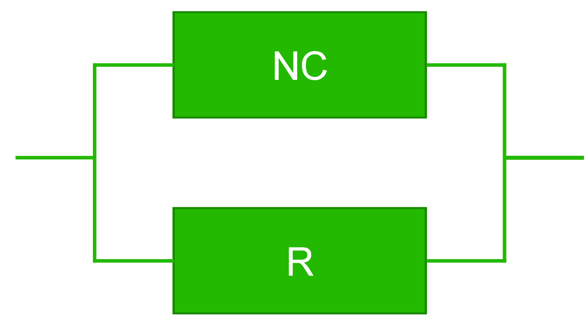


THROUGH VENTILATION (TV)



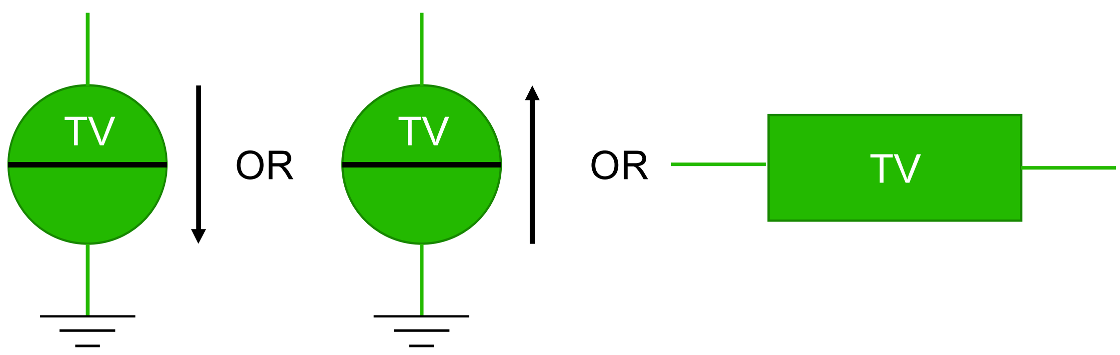
The heat exchange with the environment is the natural convection (NC) and the radiation (R). It is possible to simulate this with two resistance in parallel, one for each heat exchange. The through ventilation can be simulated as a (negative, typically the fluid has a lower temperature than the motor) heat source that removes the heat in different areas of the machine in the function of its shape and air flow and temperature, or it can be simulated with its equivalent thermal convection resistance.

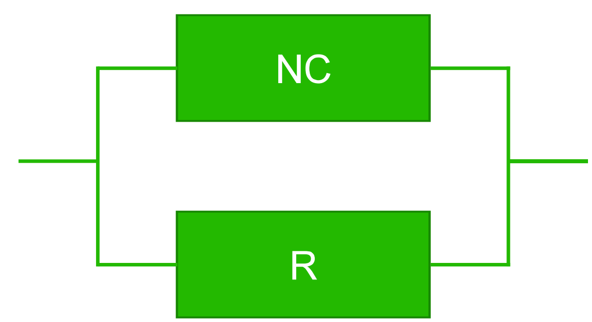




TOTALLY ENCLOSED WITH INTERNAL CIRCULATING AIR

The heat exchange with the environment is the natural convection (NC) and the radiation (R). It is possible to simulate this with two resistance in parallel, one for each heat exchange. The internal circulating area can be simulated as a heat source which can be positive or negative because the air moves the heat from one area to another. The heat will be removed from the hotter area to the colder one. It is also possible to simulate considering the different thermal convection resistance.





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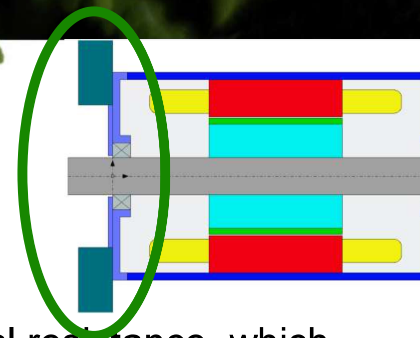
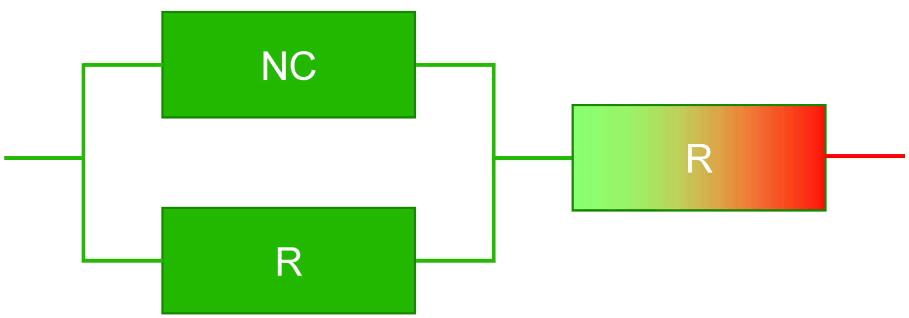
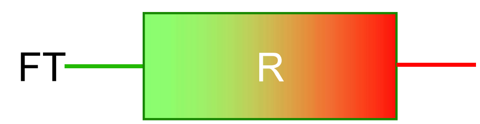
OPEN END-SHIELD COOLING



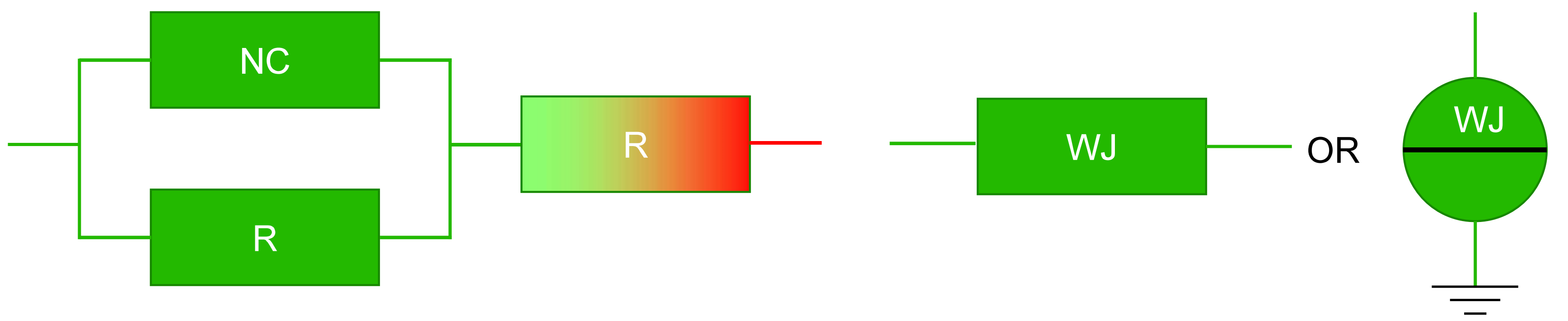
The motor exchanges the heat with the plate through an interference thermal resistance, which depends on the roughness of the two surfaces and the contact pressure. The plate exchanges the heat with the environment through natural connection and radiation. In this case, it is possible to simulate this with two resistance in parallel, one for each heat exchange. The other way for the simulation is to fix the temperature (fixed temperature, FT) of the plate to e desired one; in this case, there will be a cooling system that maintains the plate to a constant temperature.





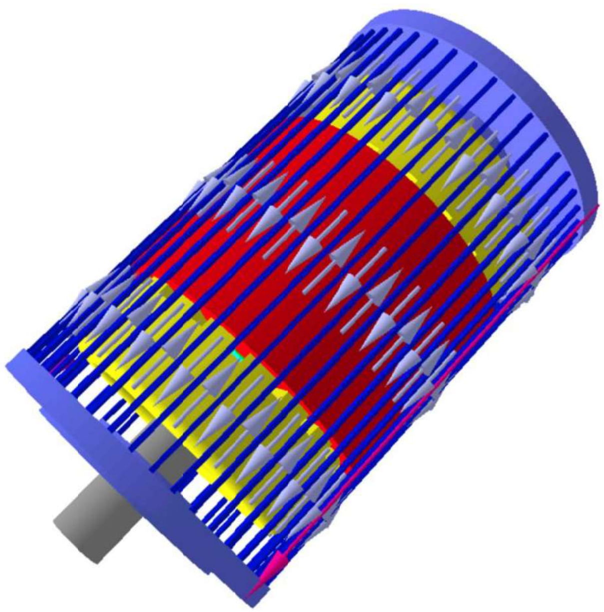
WATER JACKETS

The motor exchanges the heat with the water jacket housing through an interference thermal resistance, which depends on the roughness of the two surfaces and the contact pressure. The water jacket exchanges the heat with the environment through convection and radiation. In this case, it is possible to simulate this with two resistance in parallel, one for each heat exchange. The water jacket housing can be simulated as a negative heat source generator with a power that depends on the water and housing temperature or with its equivalent thermal convection resistance.

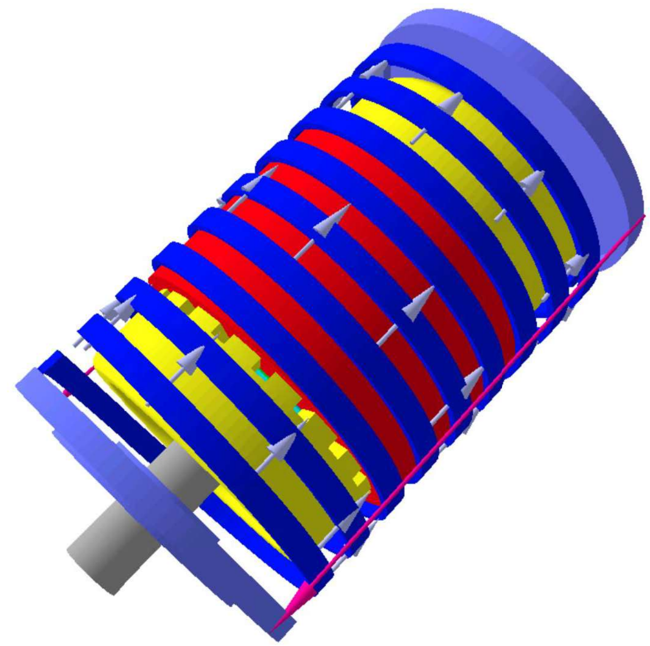


WATER JACKETS

Axial



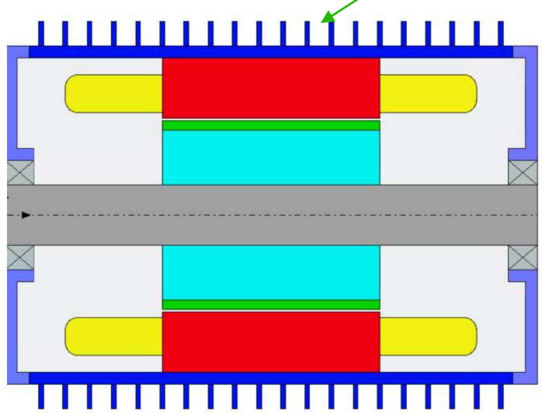
Spiral

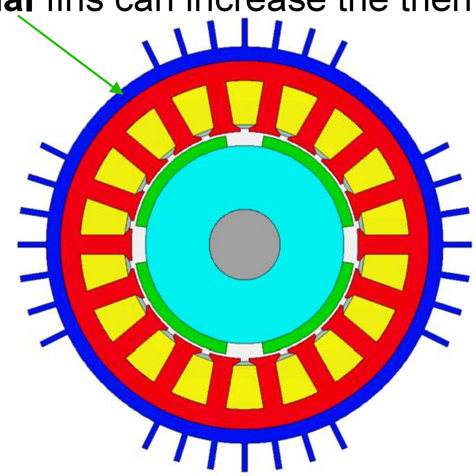


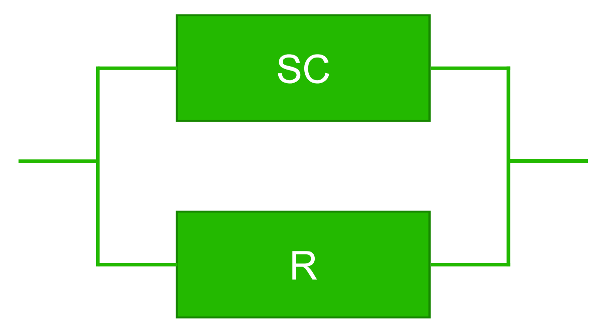
SUBMERSIBLE COOLING

It is similar to the Totally Enclosed Non-Ventilated cooling system, but the fluid is not air. Using other fluids with different properties, it is possible to increase the thermal heat exchange enhancing the heat trasmissioning and reducing the thermal resistance.

The parameters of the thermal resistances depend on the fluid properties and the shape of the housing. The adoption of **Radial** or **Axial** fins can increase the thermal heat coefficients.

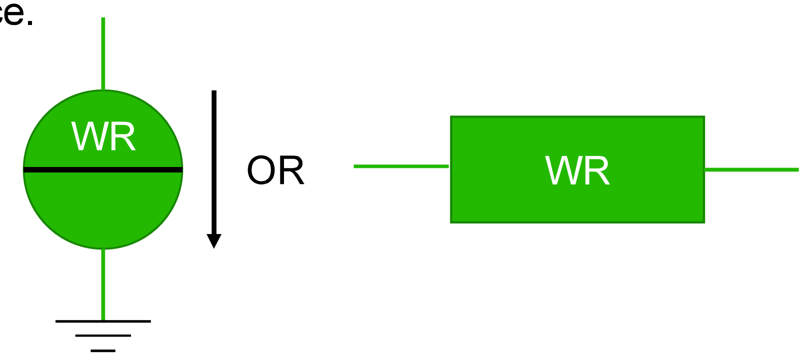






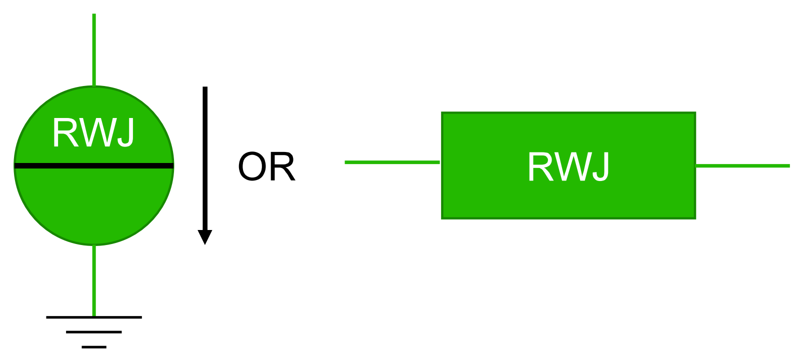
WET ROTOR

The rotor exchanges the heat with the fluid that circulating through its surface. The application o this solution is typically a pump in which the liquid is the same, which is moved by the pump connected to the rotor. This can be simulated through an equivalent thermal convective resistance. The value of the resistance depends on the fluid properties and velocity and the surface geometry of the rotor. It can be also simulated as a negative (the fluid typically has a temperature lower than the rotor) heat source generator with a power that depends on the fluid properties, velocity and temperature; and rotor geometry surface.



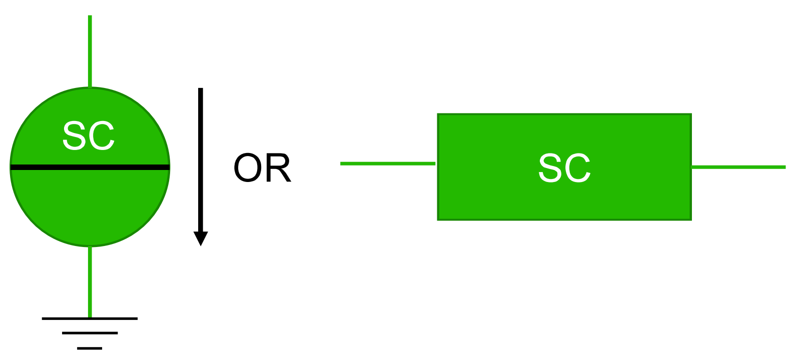
ROTOR WATER JACKET

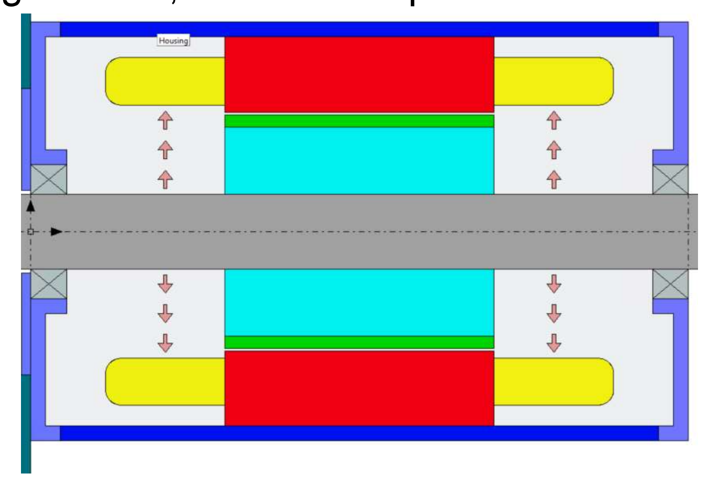
The rotor exchanges the heat with the fluid that circulating inside the rotor. There is no dedicated housing for the water circulating, but some ducts have been created for the liquid circulation. This can be simulated through an equivalent thermal convective resistance. The value of the resistance depends on the fluid properties and velocity and the surface geometry of the rotor. It can be also simulated as a negative (the fluid typically has a temperature lower than the rotor) heat source generator with a power that depends on the fluid properties, velocity and temperature; and rotor geometry surface.



SPRAY COOLING

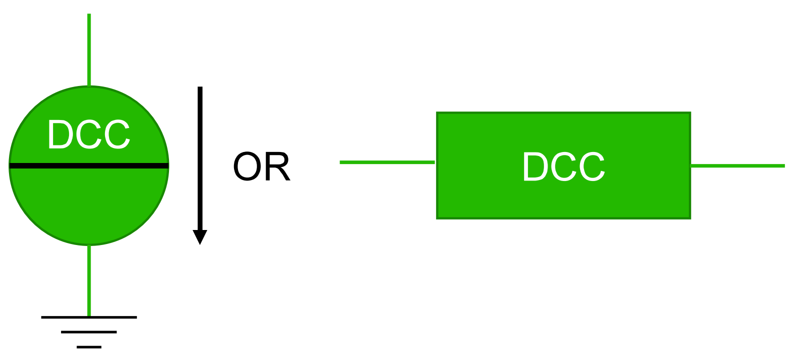
The fluid which is typically used is oil. The oil is atomized adopting a nozzle and breaks into small droplets. With this technology, the end windings (the hottest point in the machine) are directly cooled by the spray. This allows to strongly reduce the winding hotspot temperature. The spray cooling can be modeled through an equivalent (negative) heat source generator, or with an equivalent convection resistance.



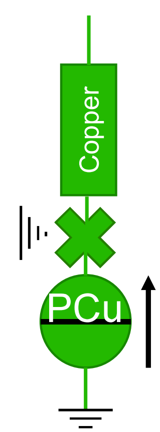


DIRECT CONDUCTOR COOLING

There is a water channel (typically made in stainless steel) inside the slot close to the conductor. This guarantees to have the cooling system closest to the highest heat generation (Joule losses). This cooling system can be simulated as equivalent convective thermal resistance, which is a function of the fluid velocity and properties and the channel geometry, or with an equivalent (negative) heat generator.



THERMAL NETWORK MODEL



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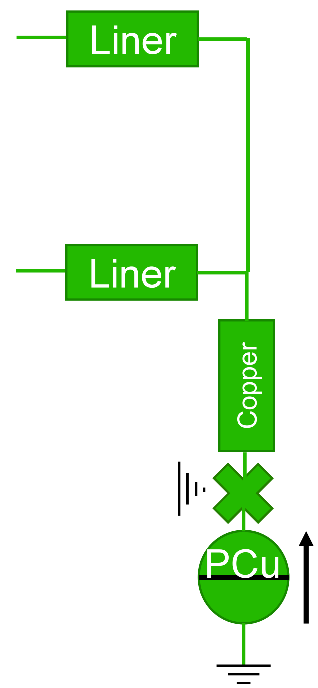

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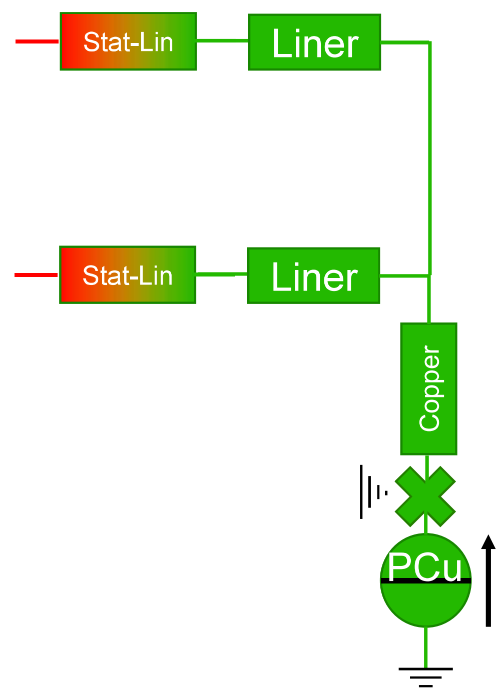

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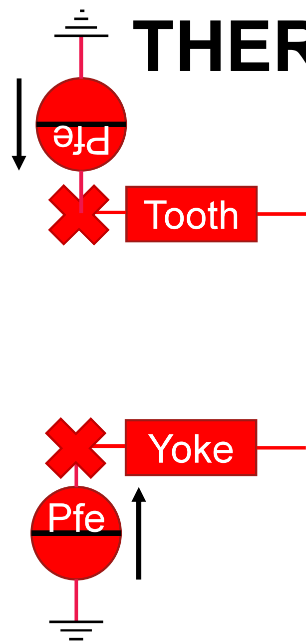

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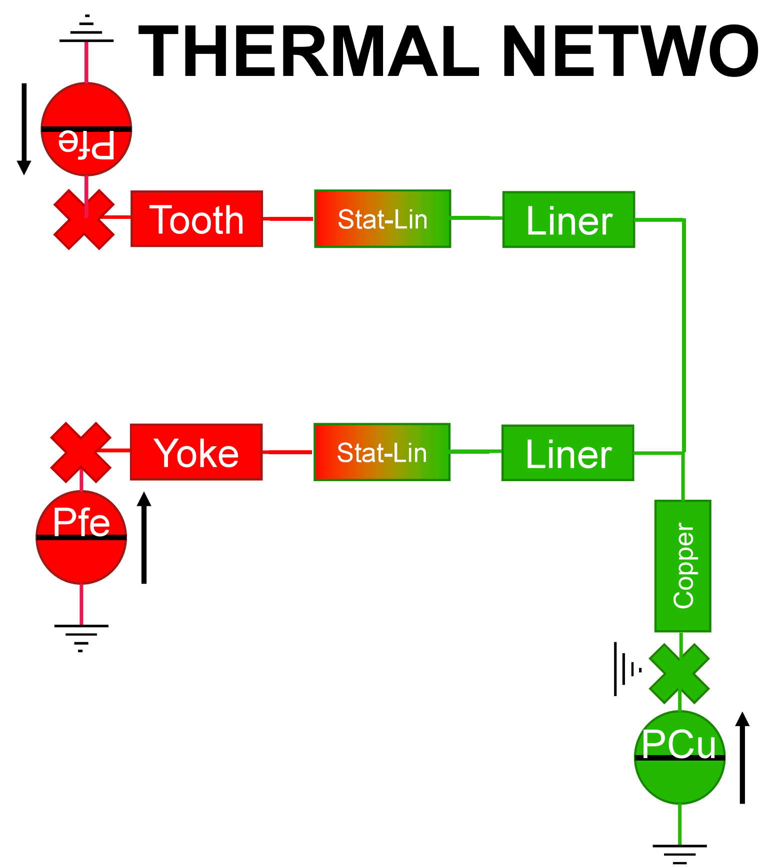

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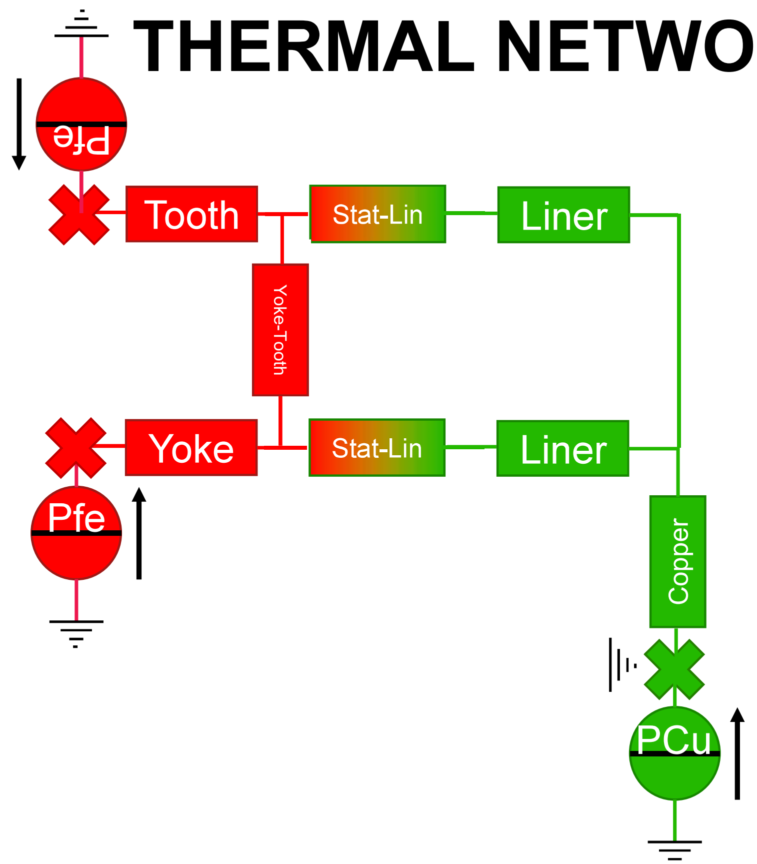

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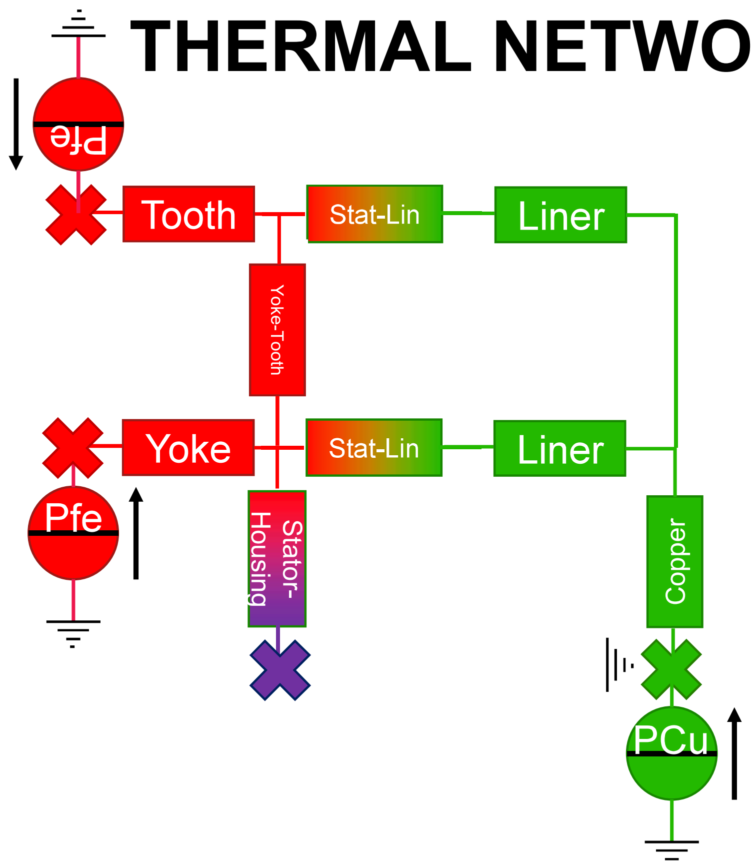

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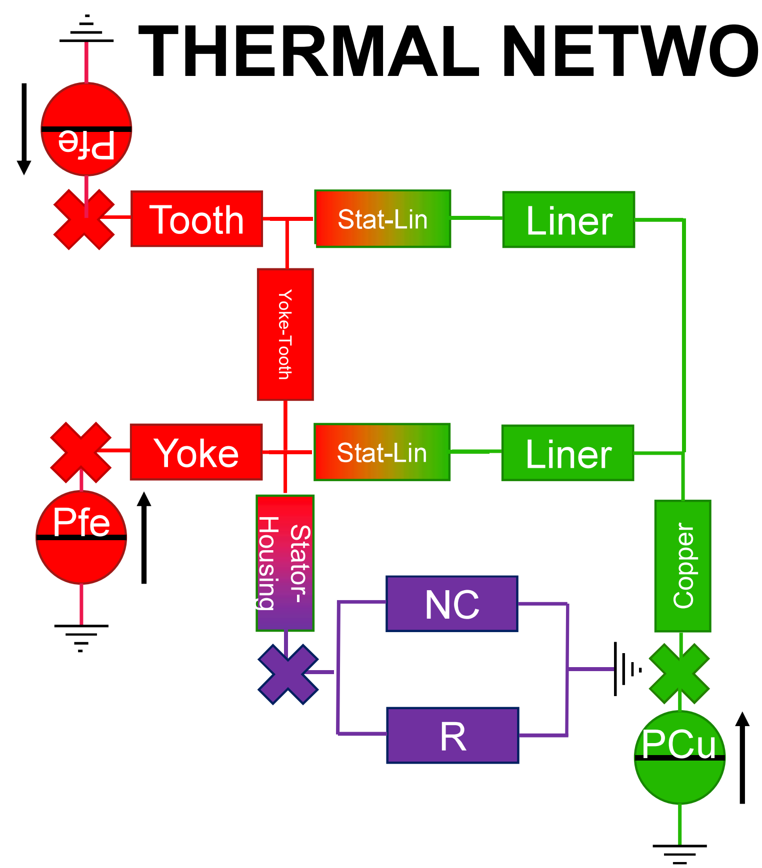

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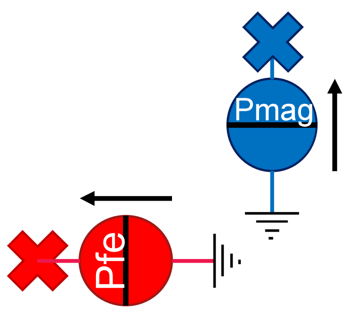

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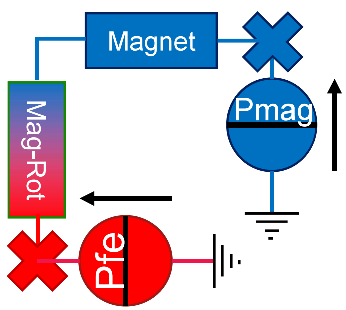

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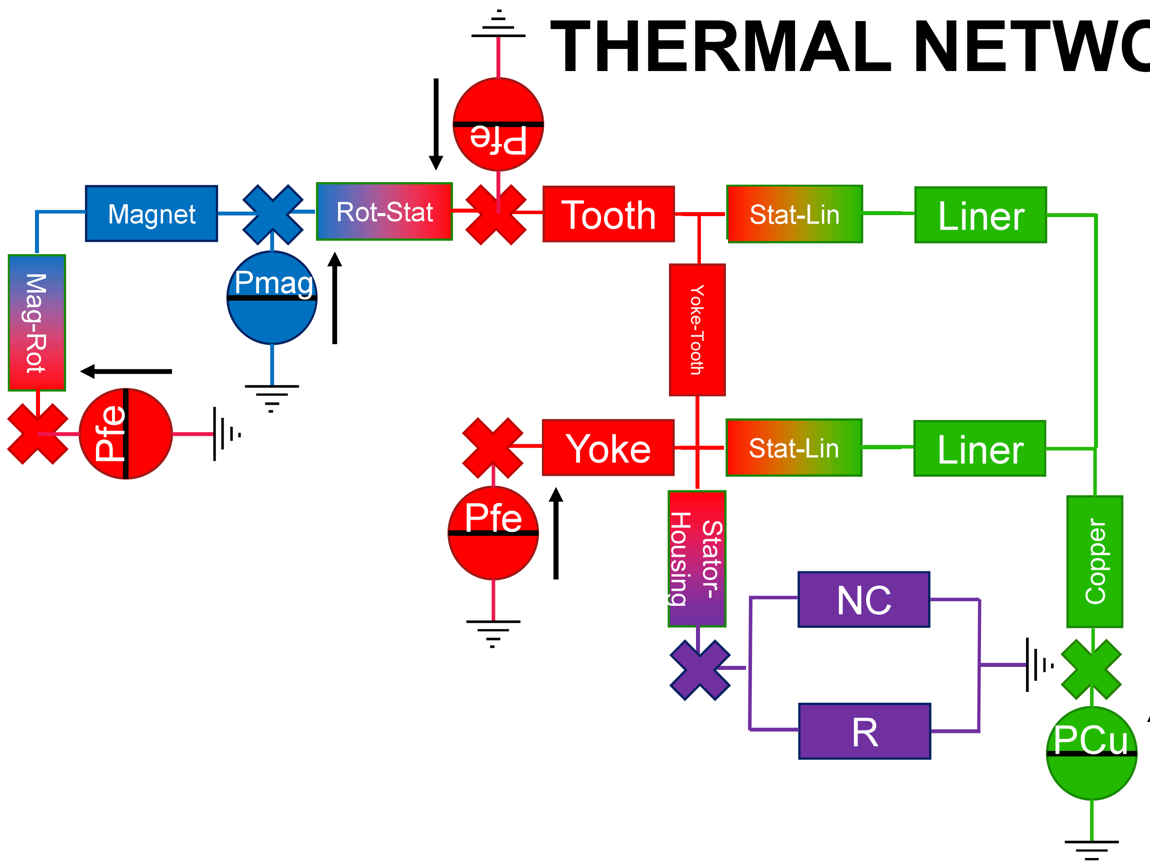

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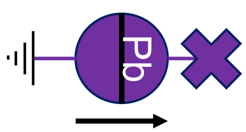

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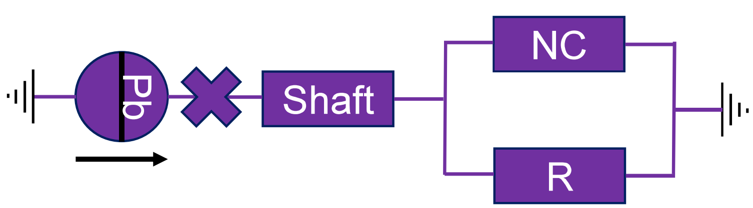

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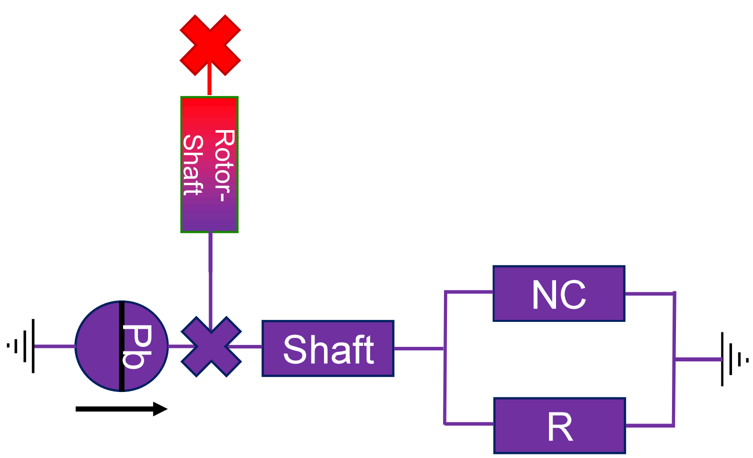

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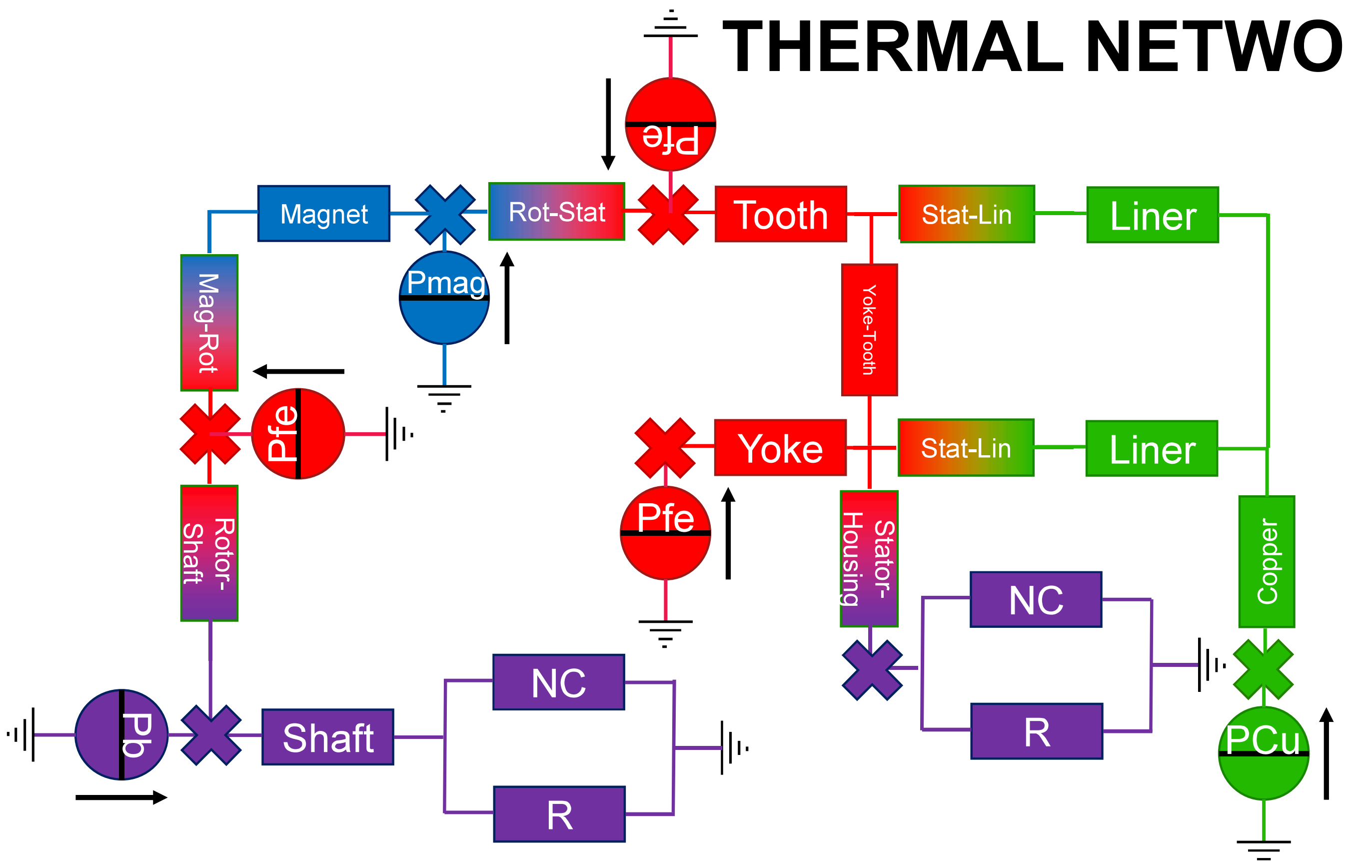
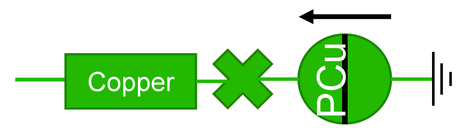
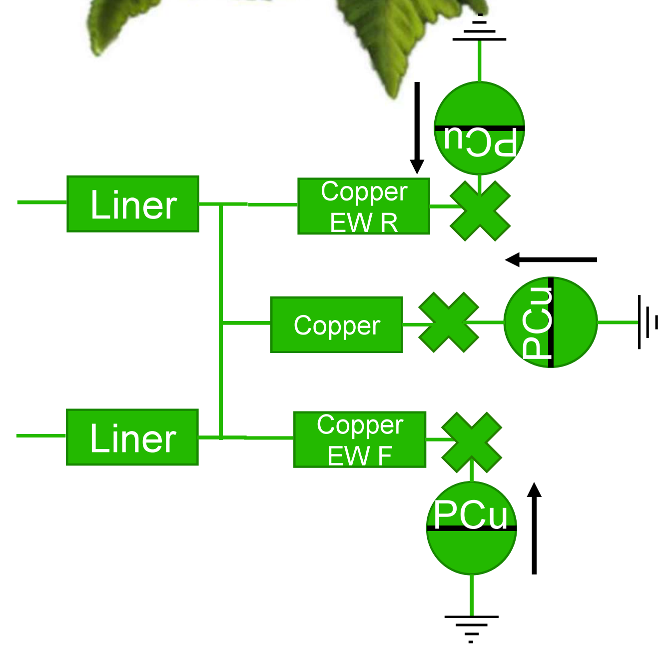
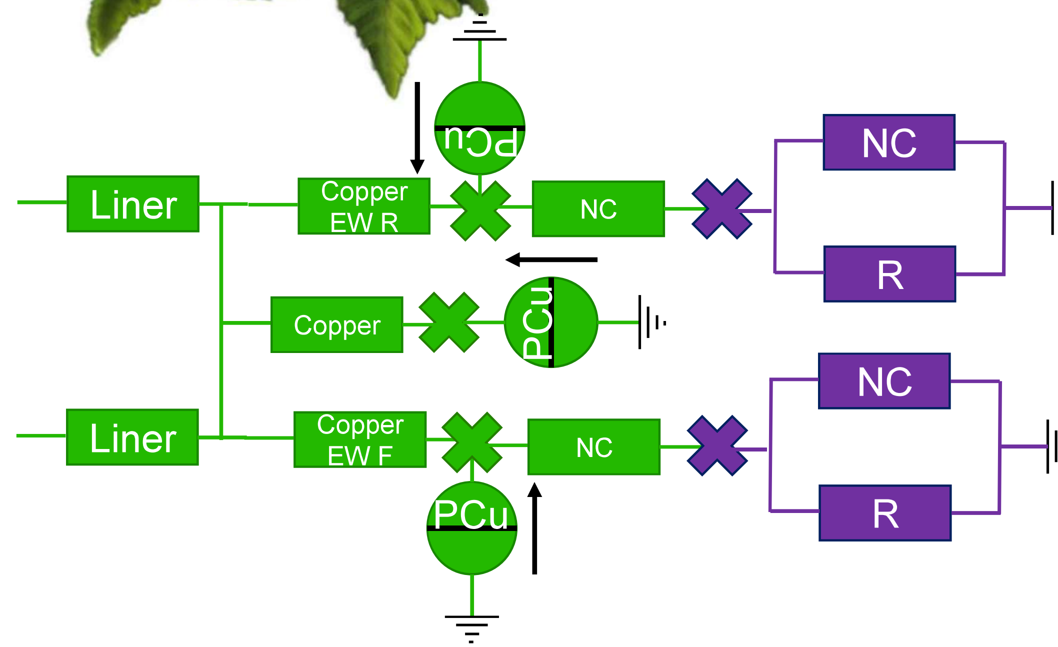
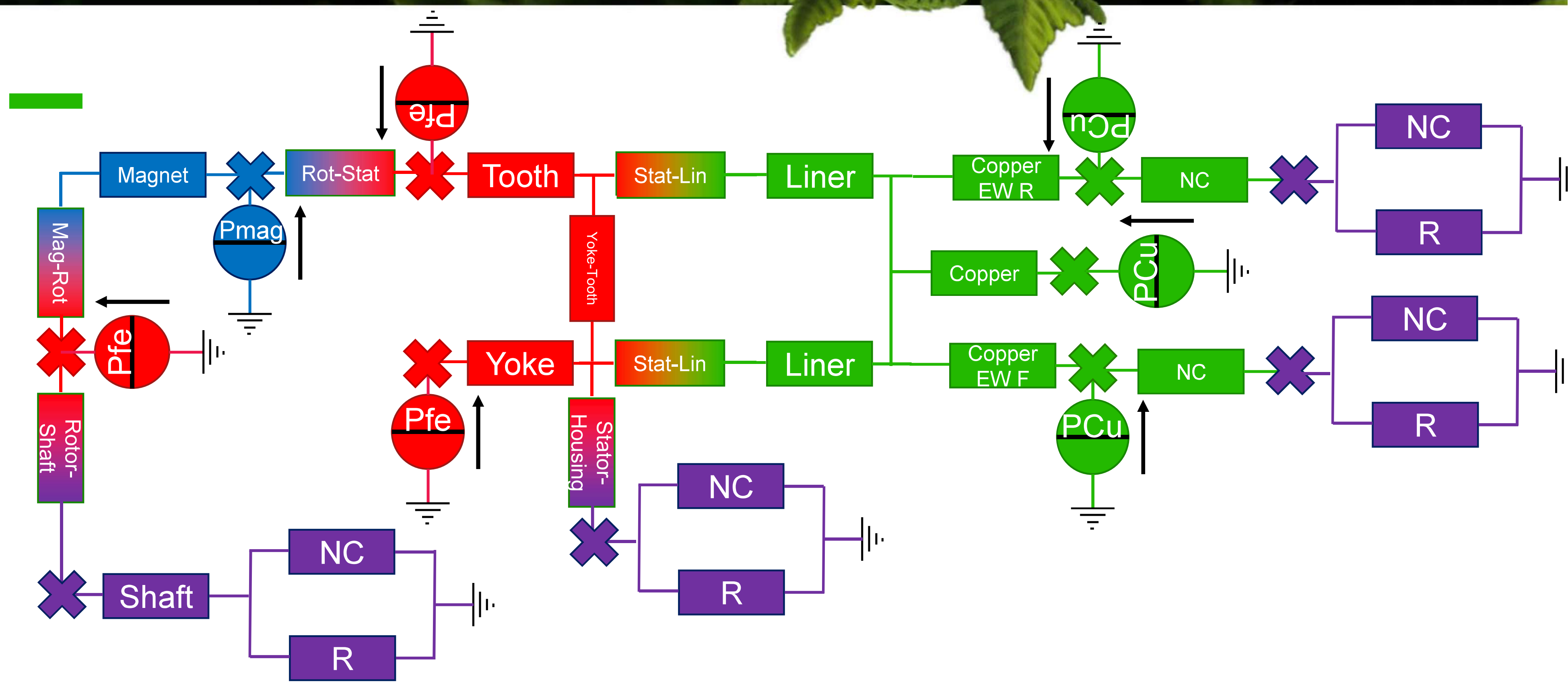



Copper
PCu

LUT University



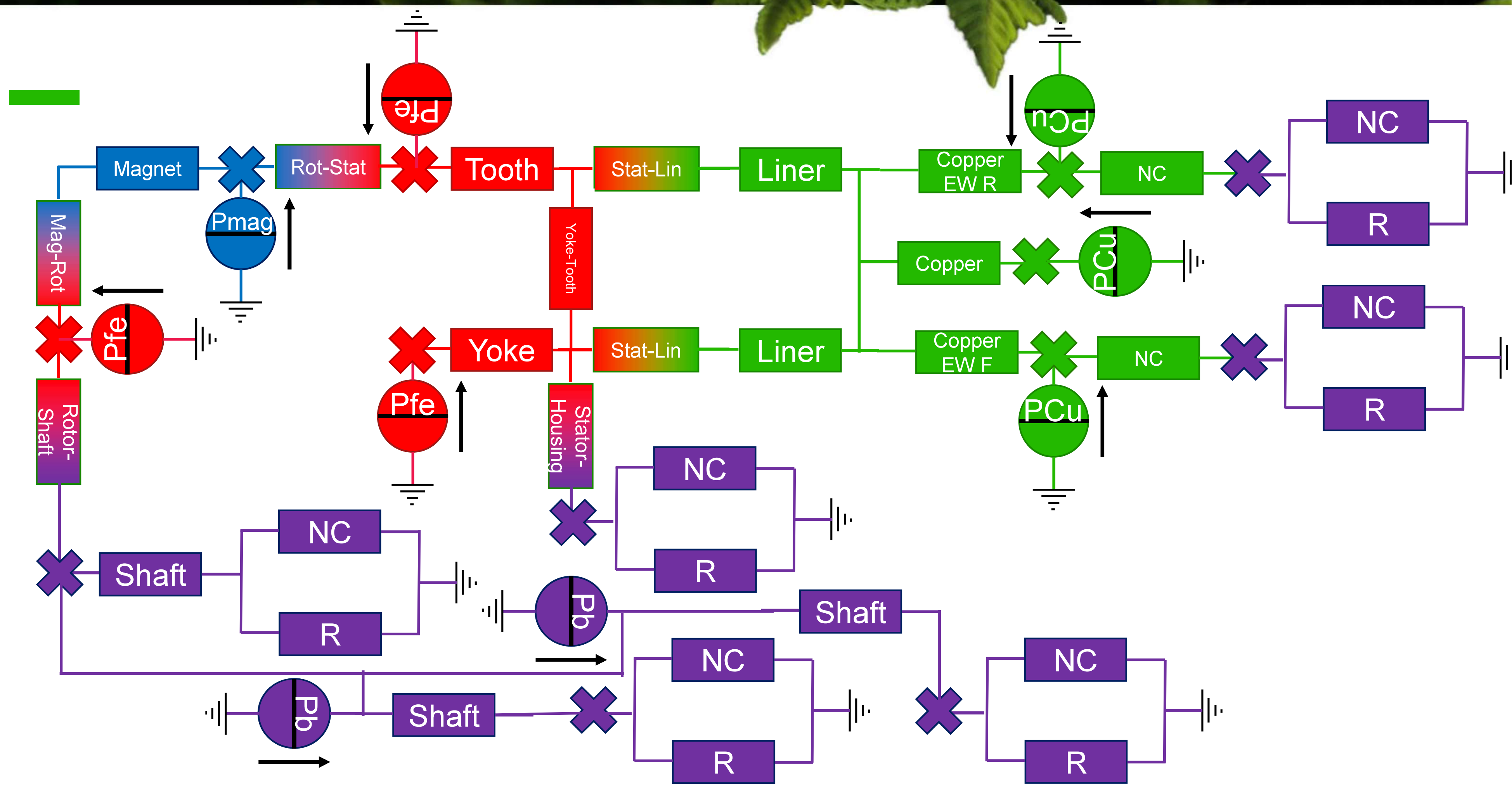

Liner
Liner
Copper EW R
Copper
Copper EW F
PCu
PCu
PCu
NC
NC
NC
R
NC
R



Magnet
Rot-Stat
Tooth
Stat-Lin
Liner
Copper EW R
NC
NC
R
Pfe
Pmag
Mag-Rot
Pfe
Yoke-Tooth
Copper
PCu
PCu
Yoke
Stat-Lin
Liner
Copper EW F
NC
NC
R
Rotor-Shaft
Pfe
PCu
Stator-Housing
NC
R
Shaft
NC
R

TOTALLY ENCLOSED NON-VENTILATED

LUT University



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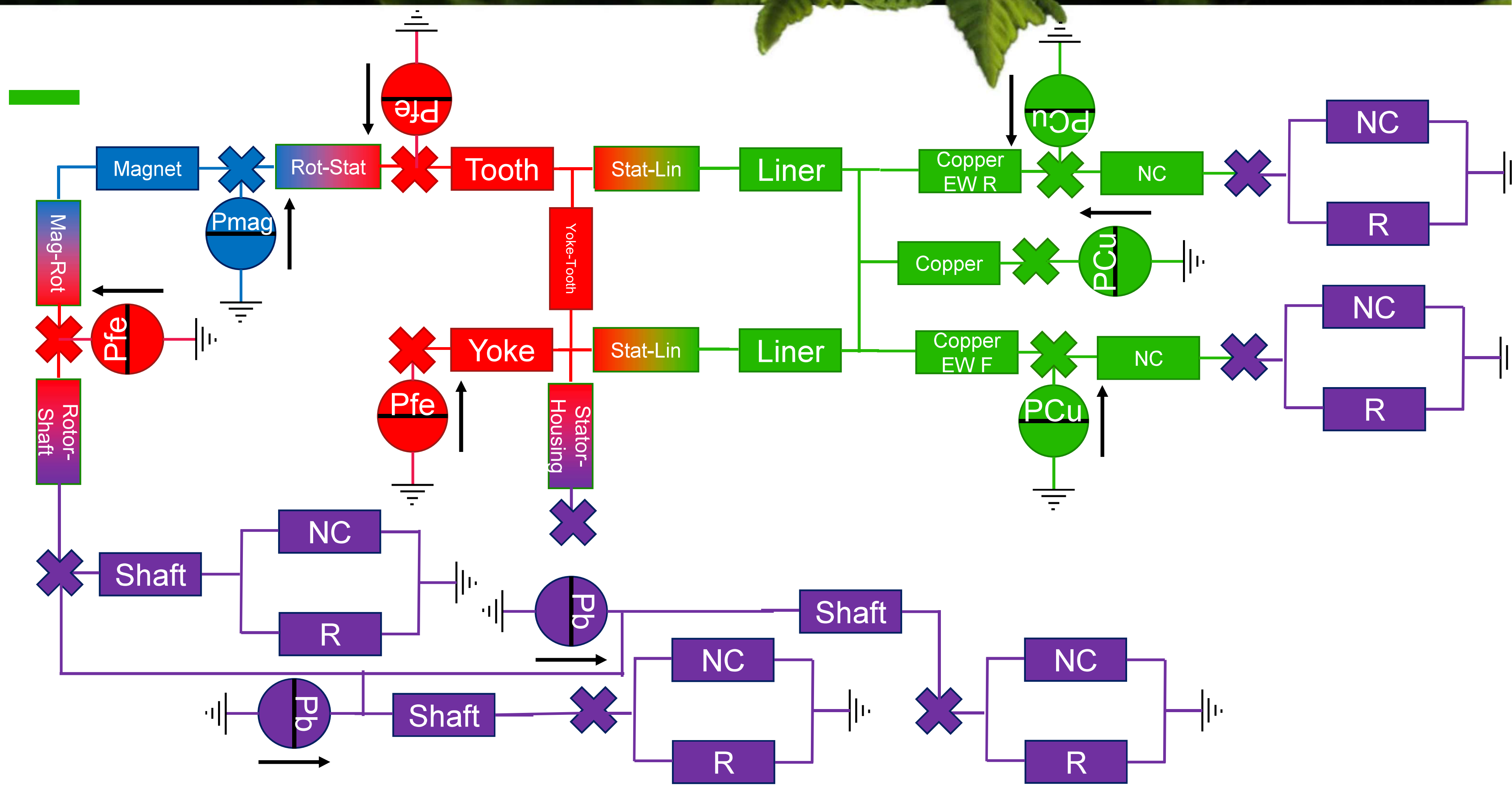
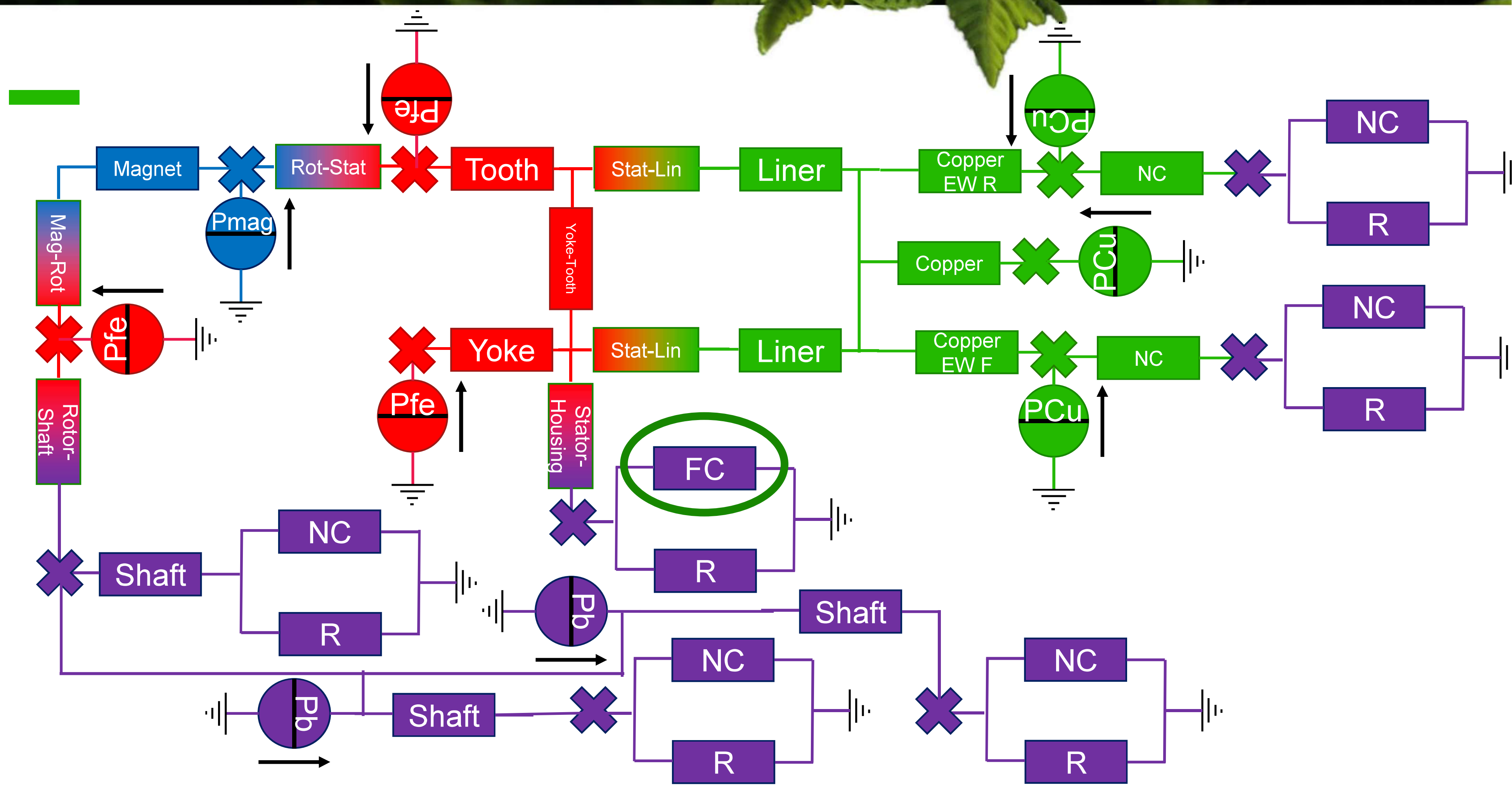


TOTALLY ENCLOSED FAN-COOLED

LUT University



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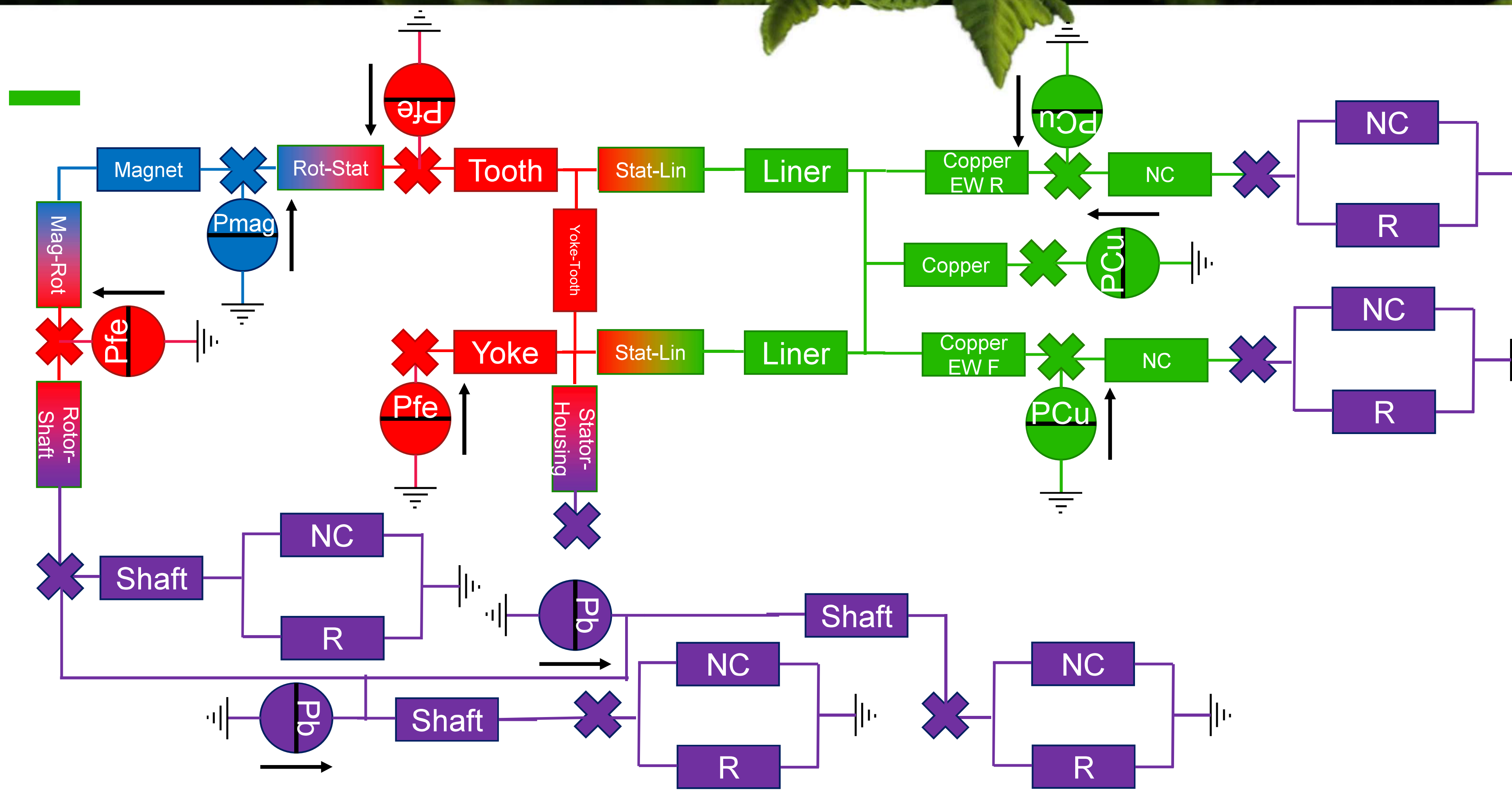

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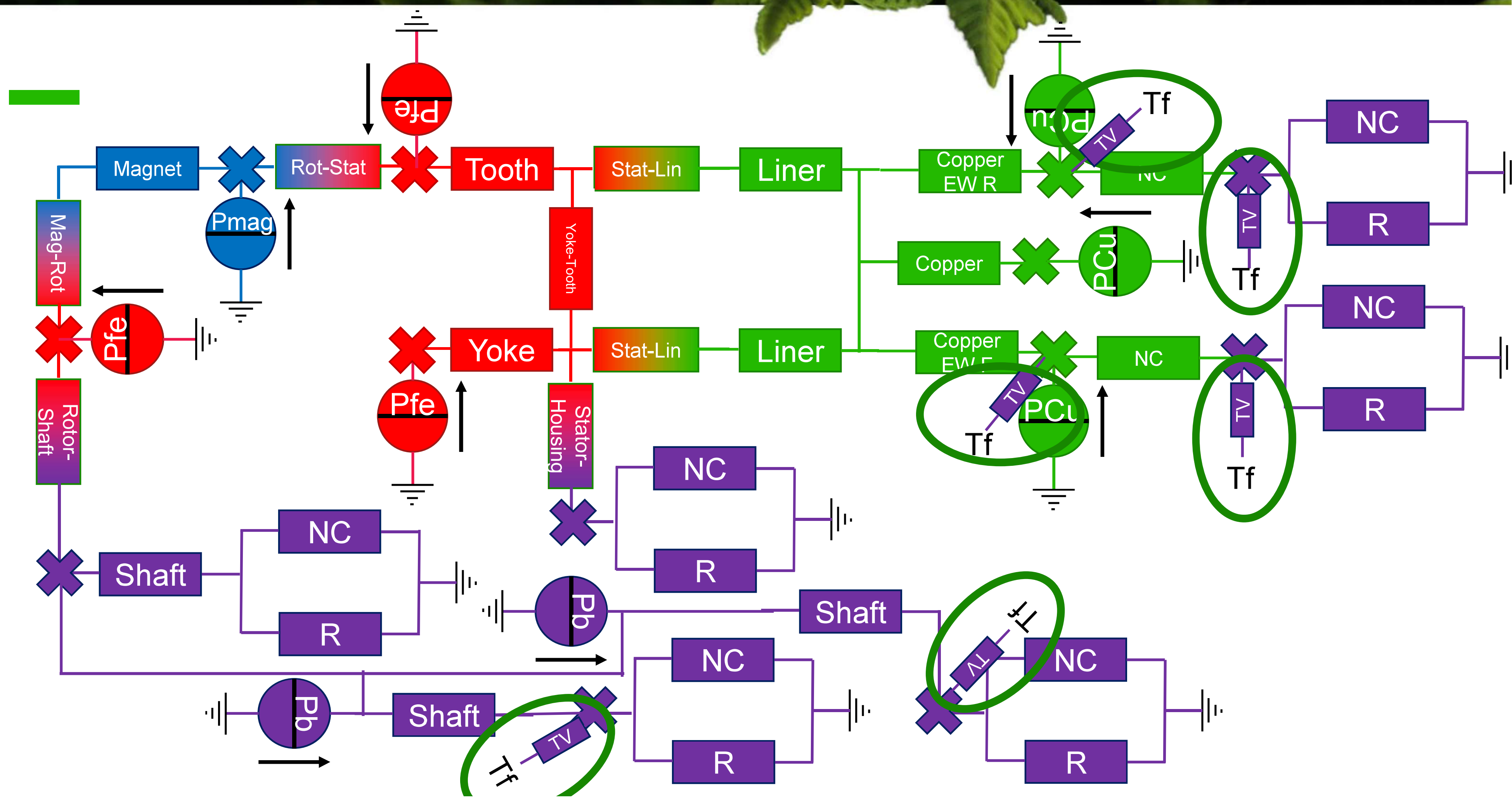
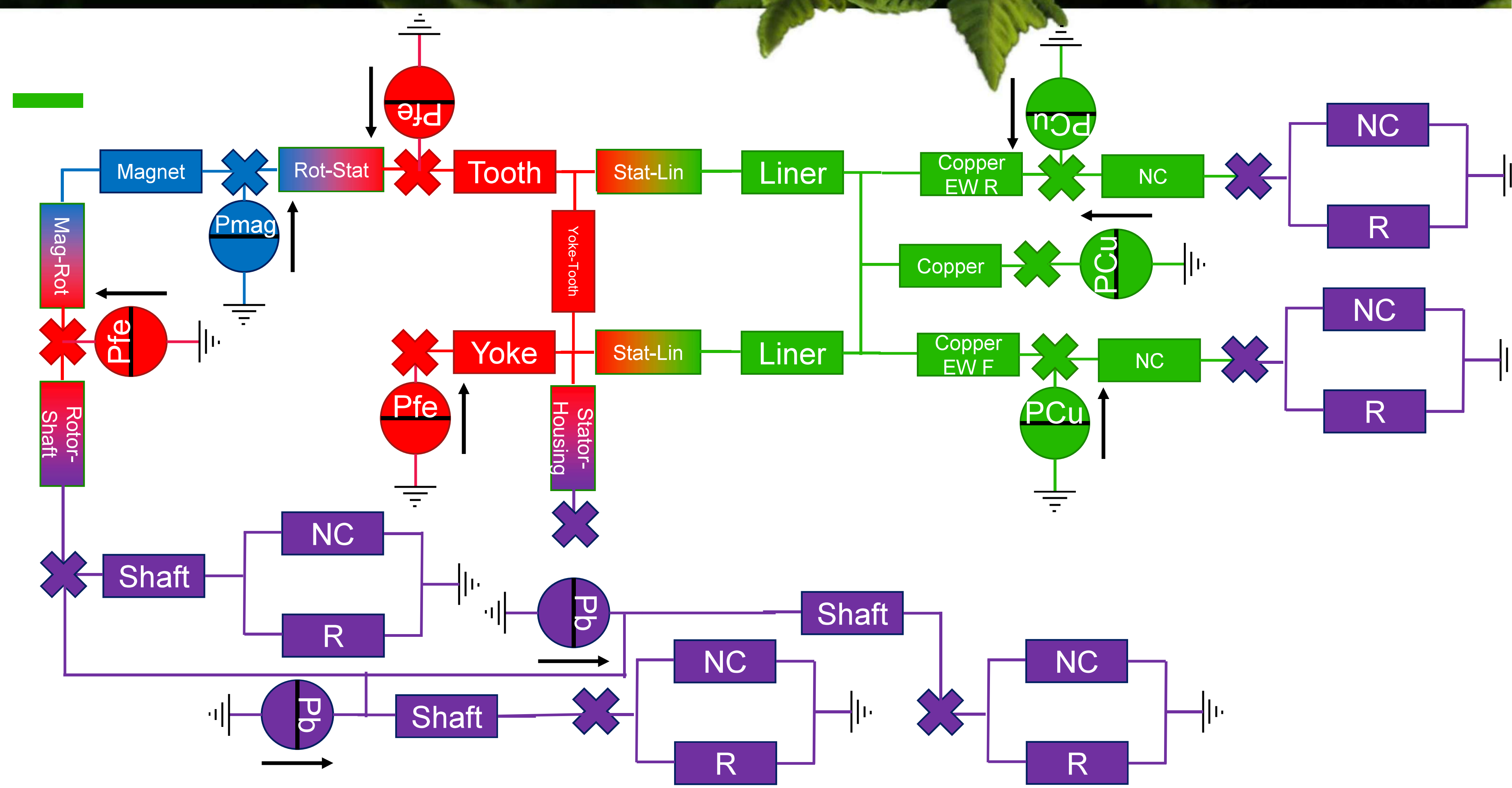
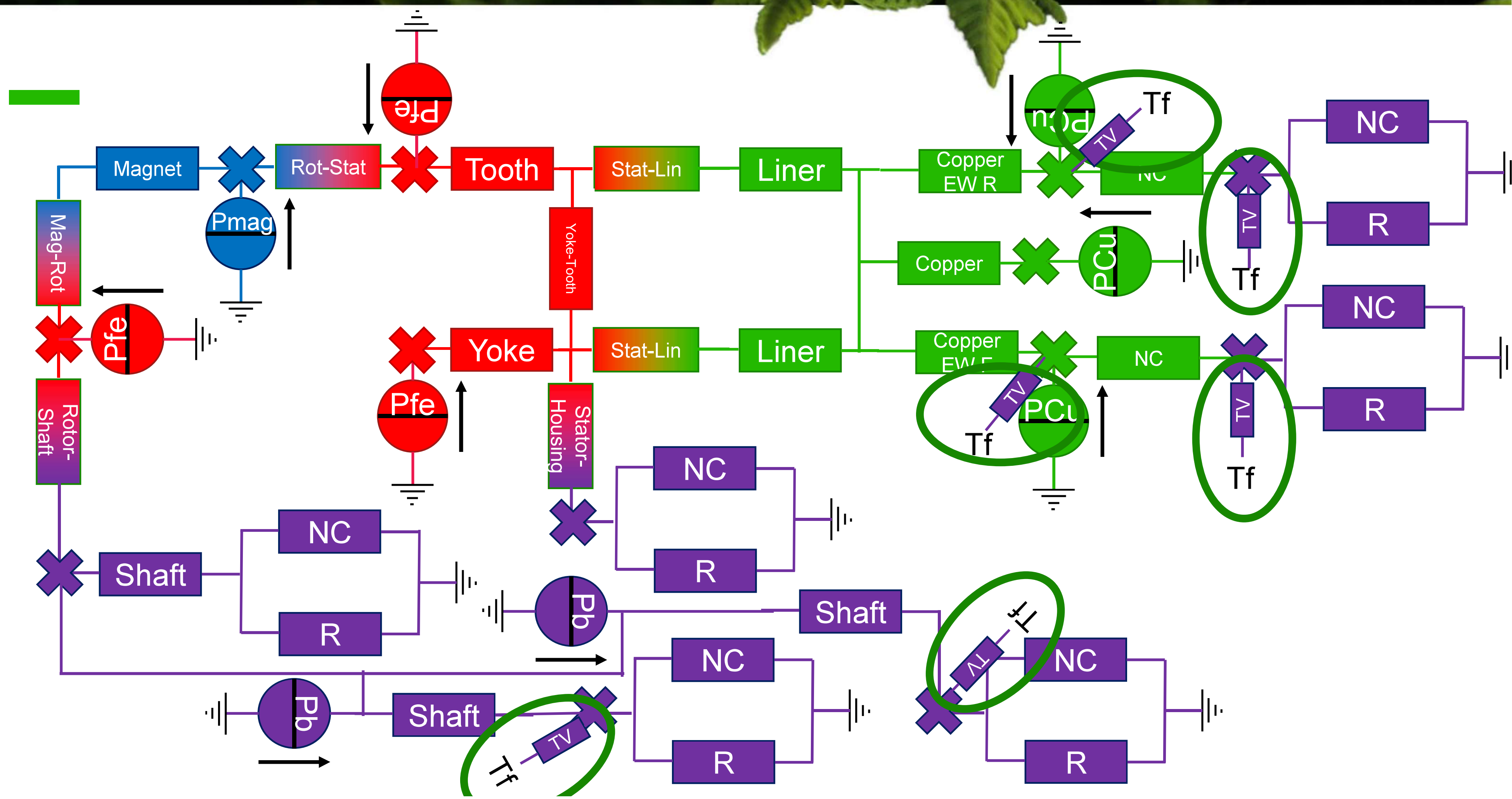


TOTALLY ENCLOSED WITH INTERNAL CIRCULATING AIR

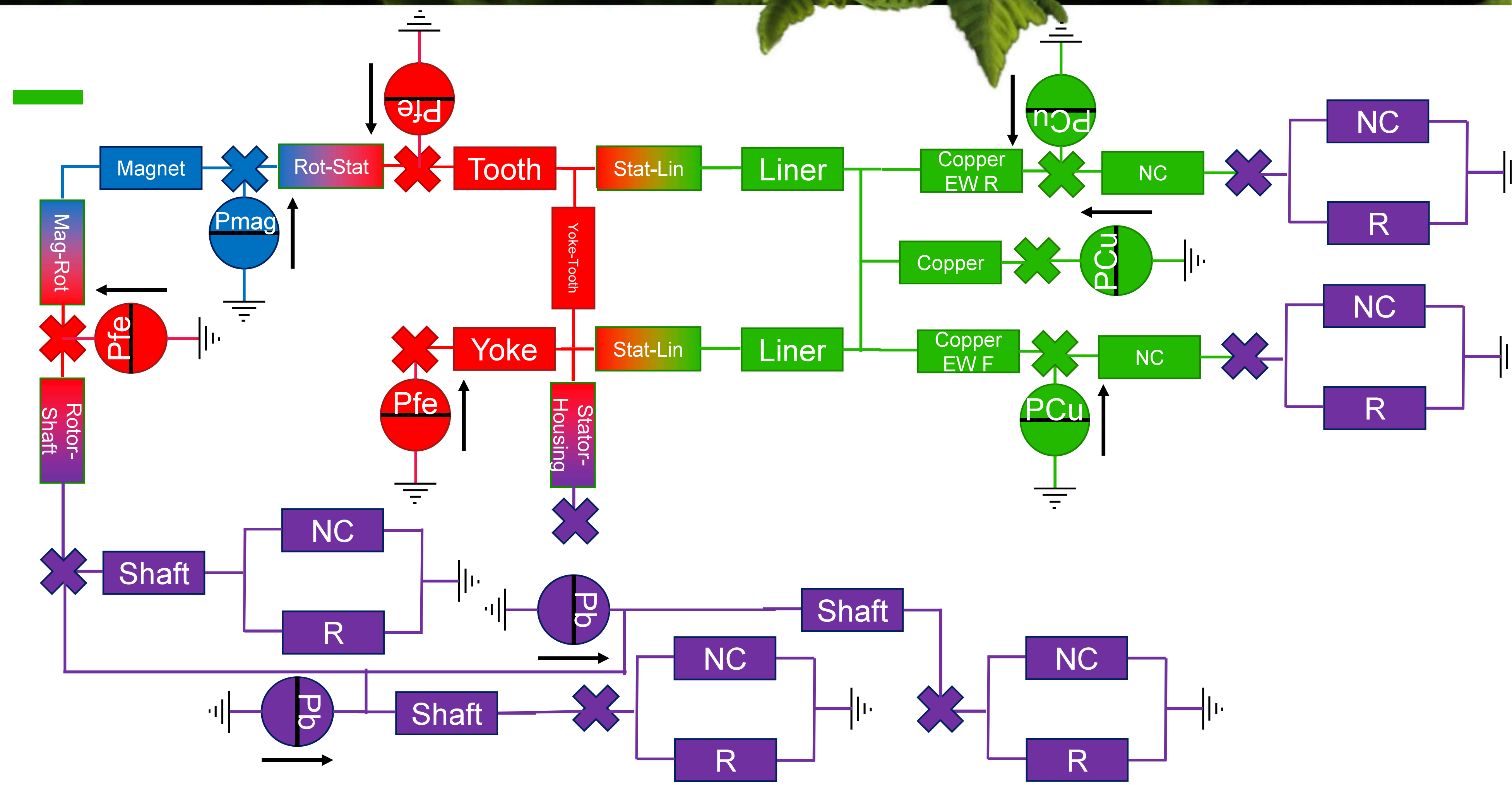
University



TOTALLY ENCLOSED WITH INTERNAL CIRCULATING AIR

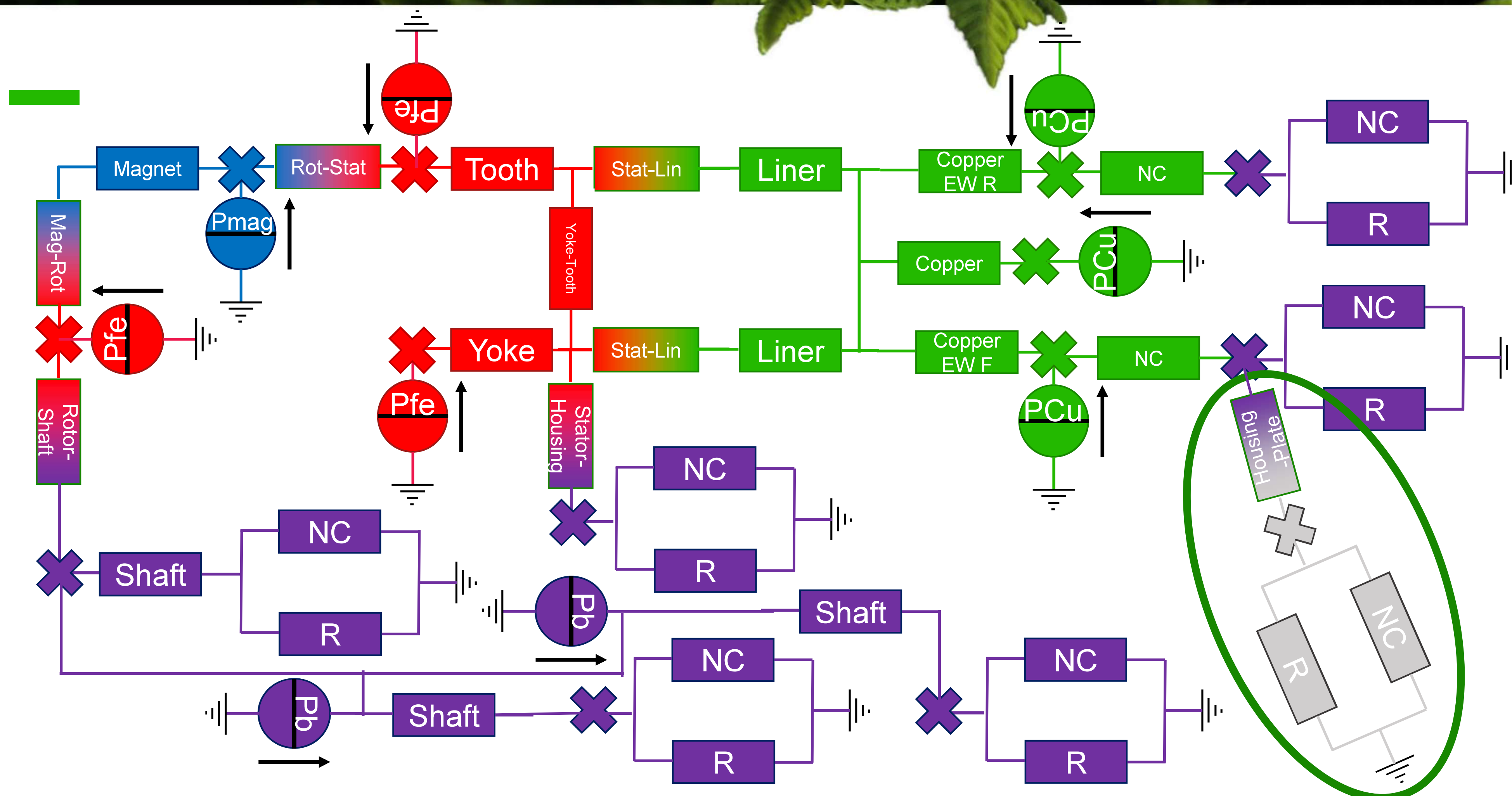


OPEN END-SHIELD COOLING

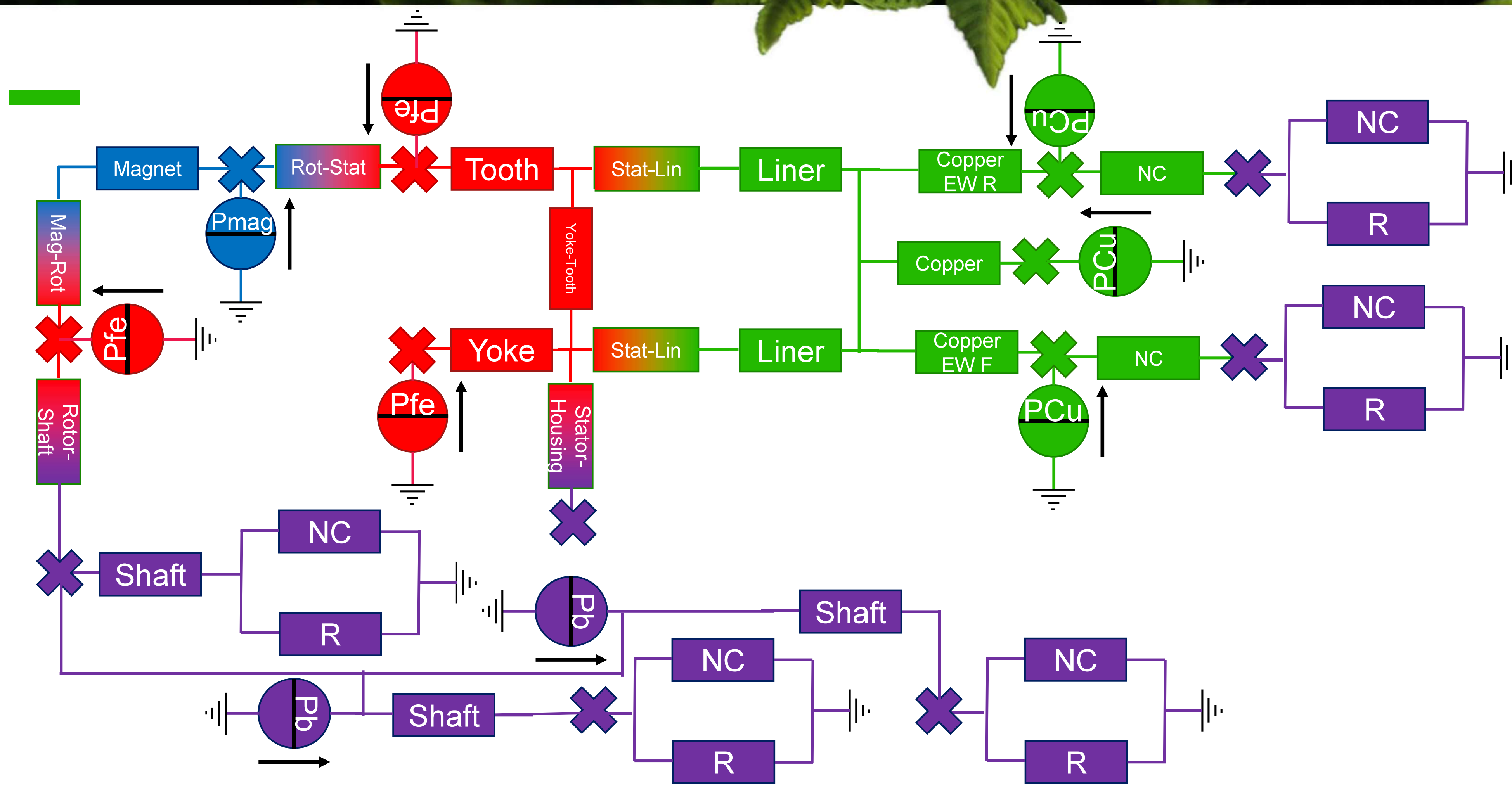


OPEN END-SHIELD COOLING

LUT University



WATER JACKETS



WATER JACKETS

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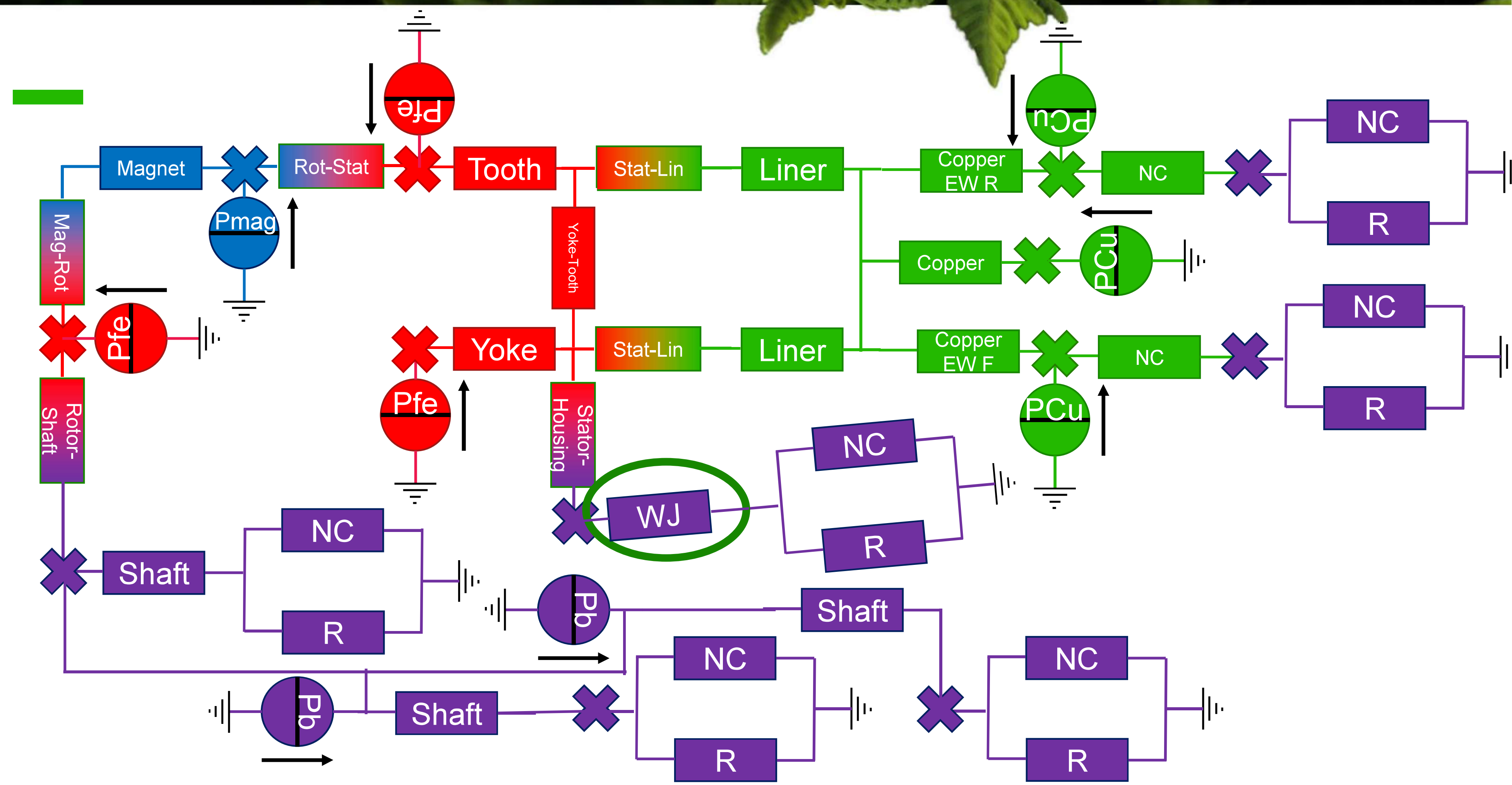
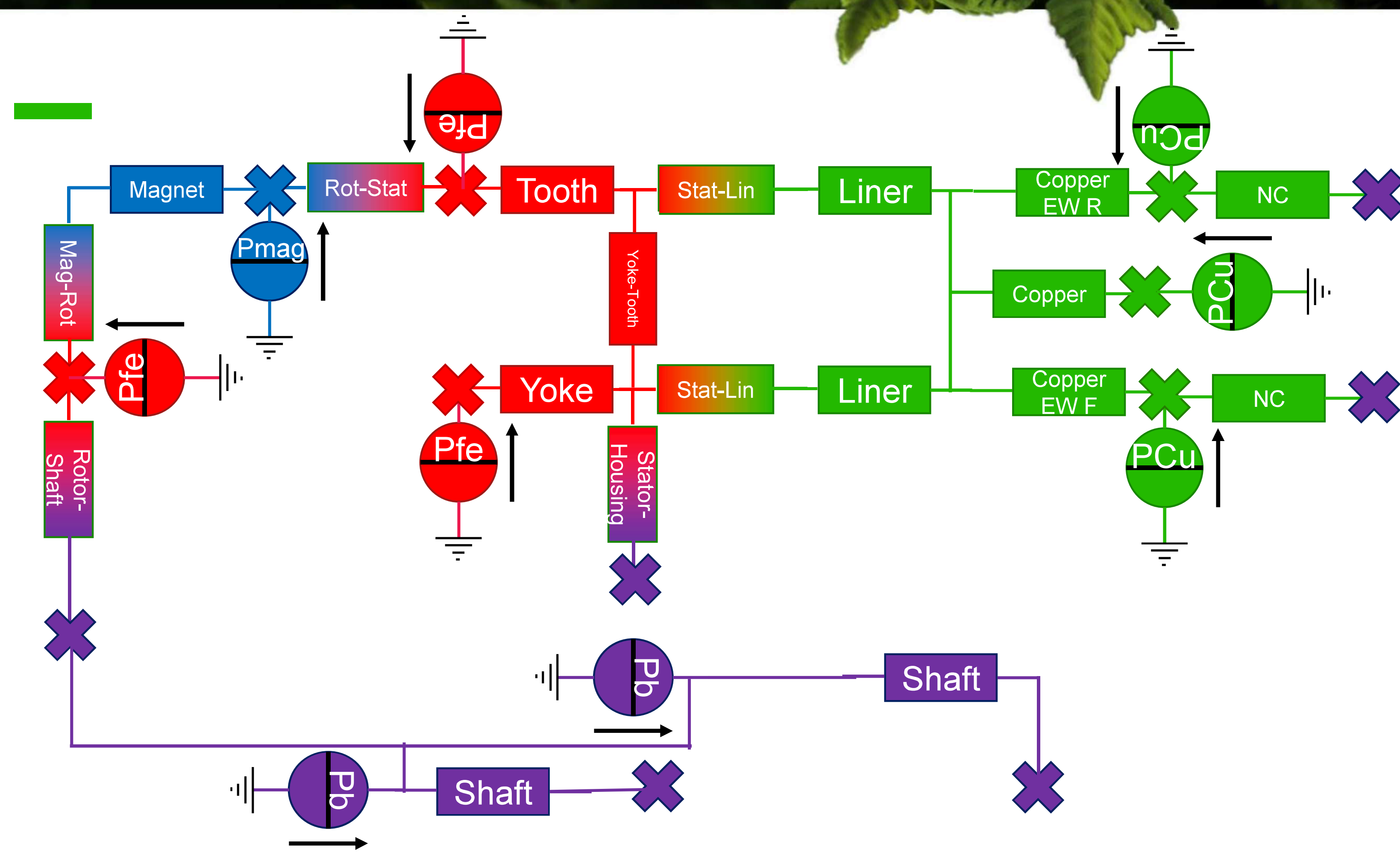


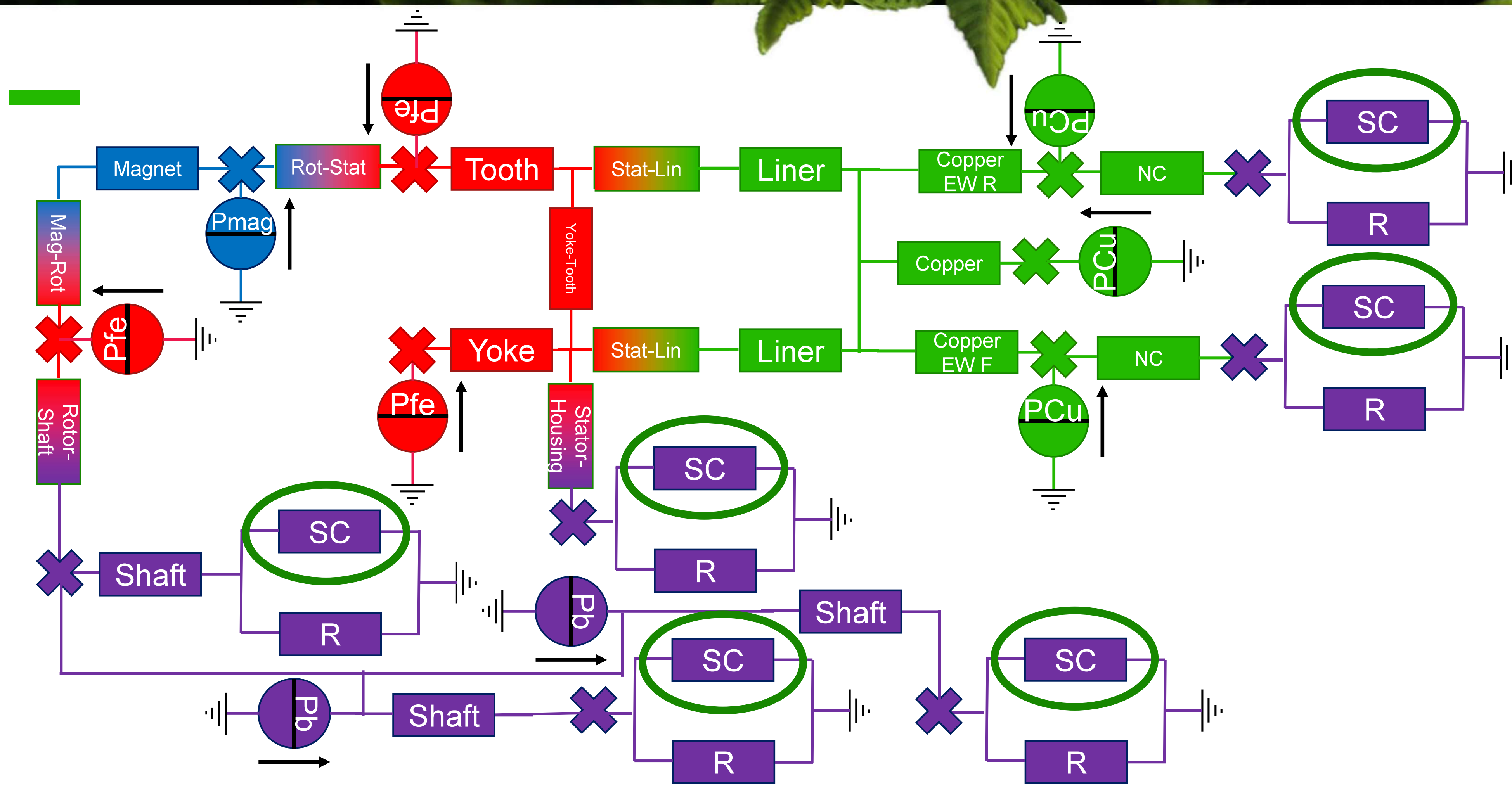
SUBMERSIBLE COOLING (SC)

LUT University



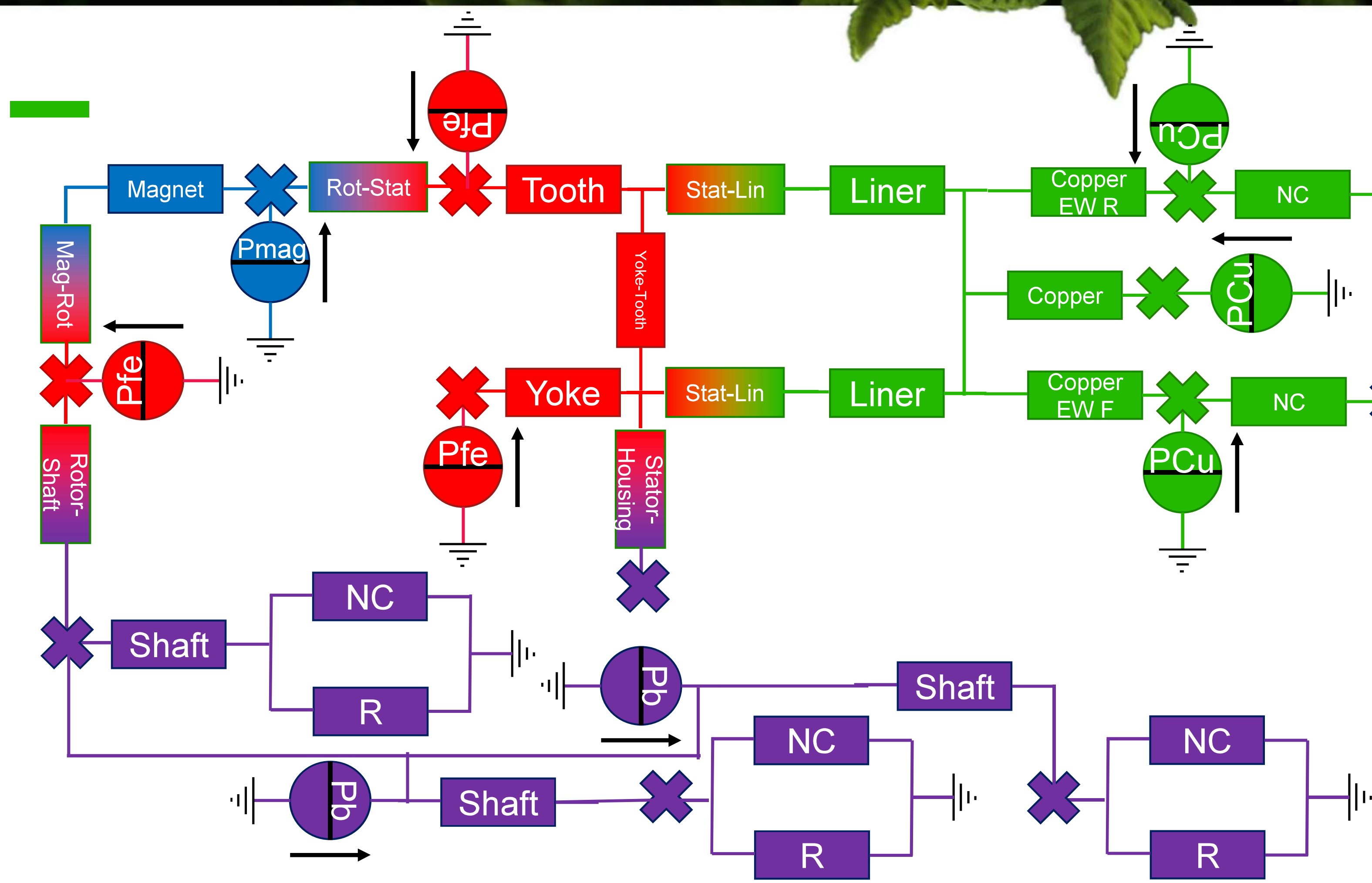
SUBMERSIBLE COOLING (SC)

LUT University



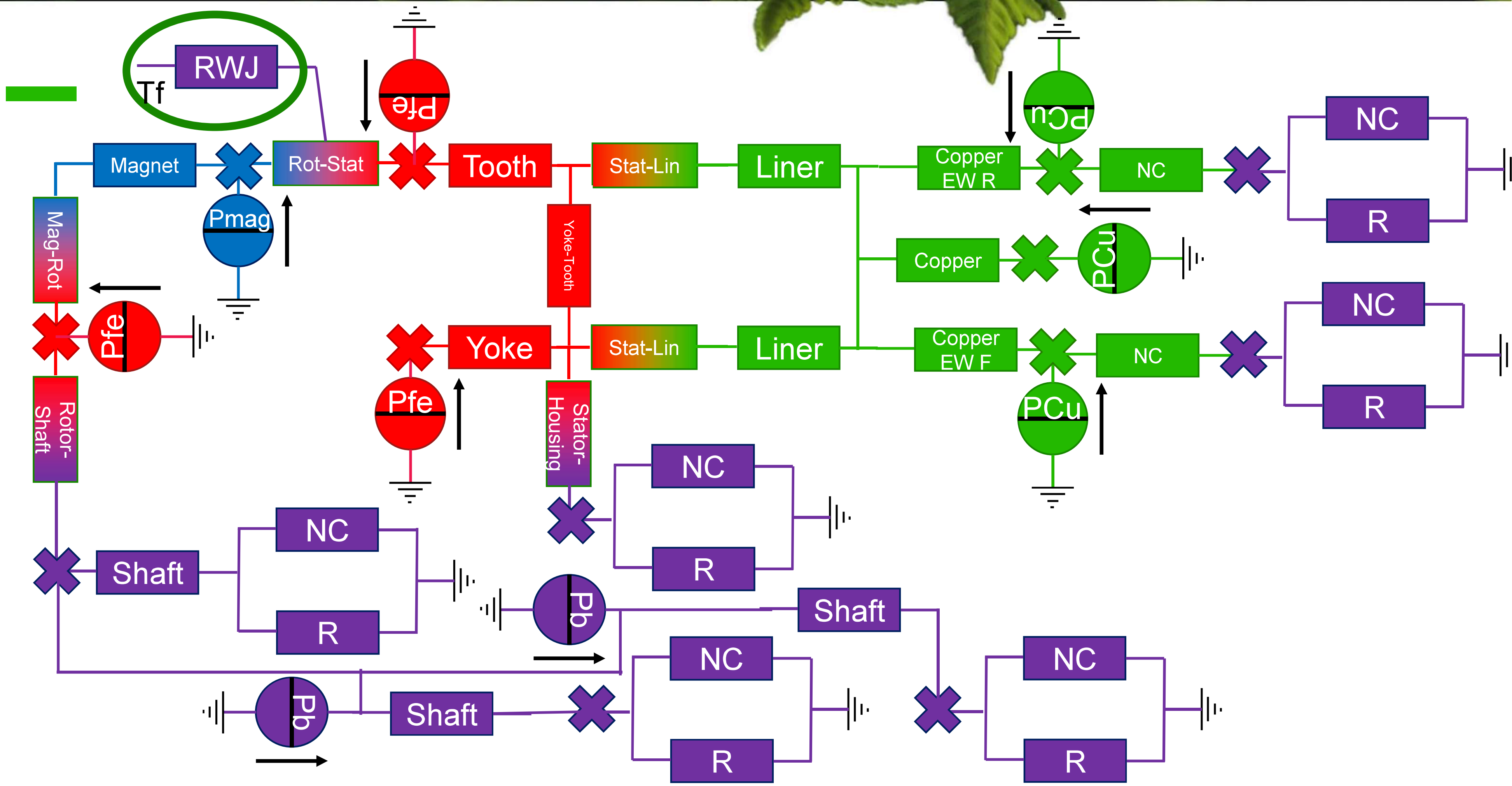
WET ROTOR

LUT University

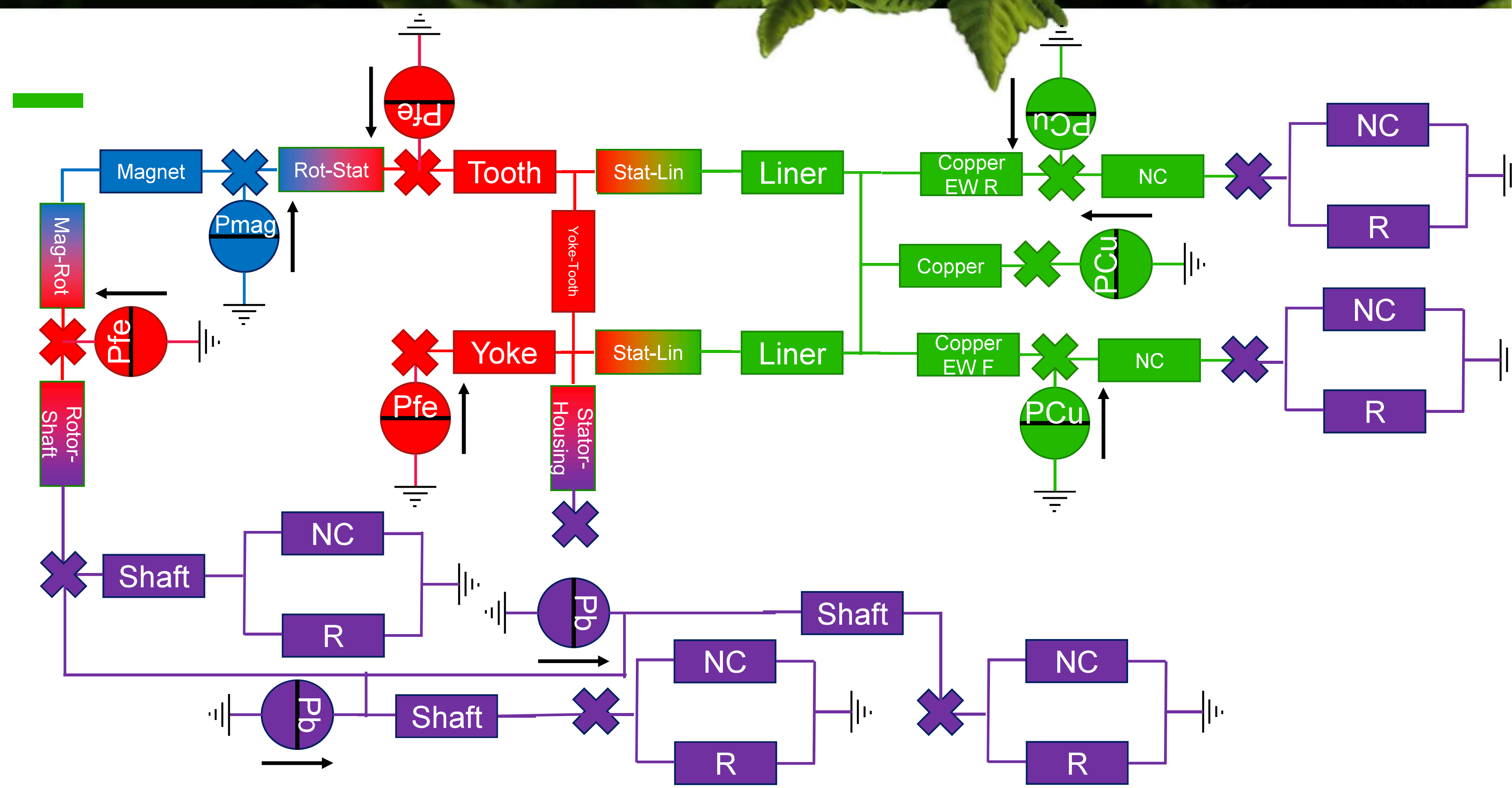


WET ROTOR

LUT University



ROTOR WATER JACKET



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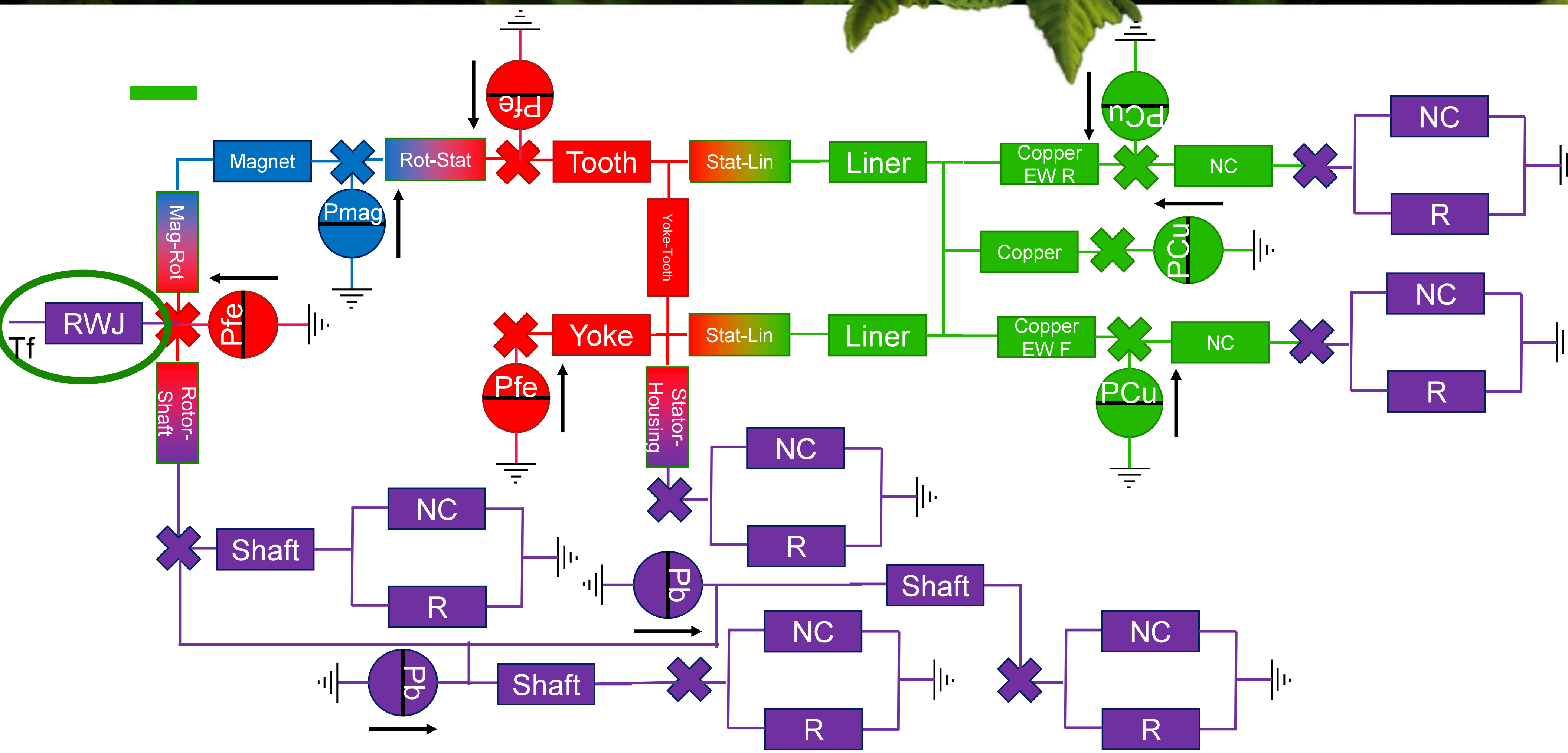

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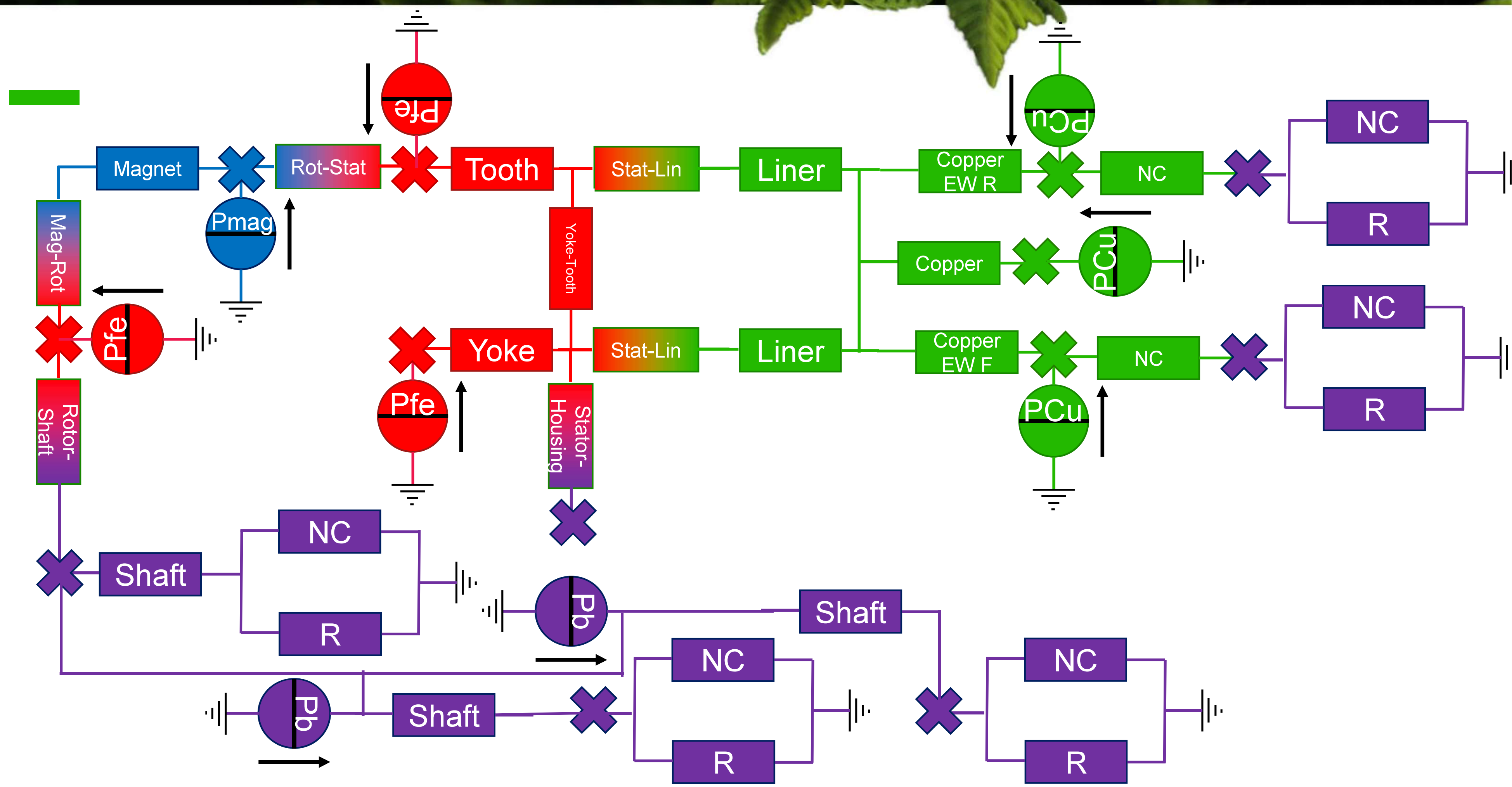
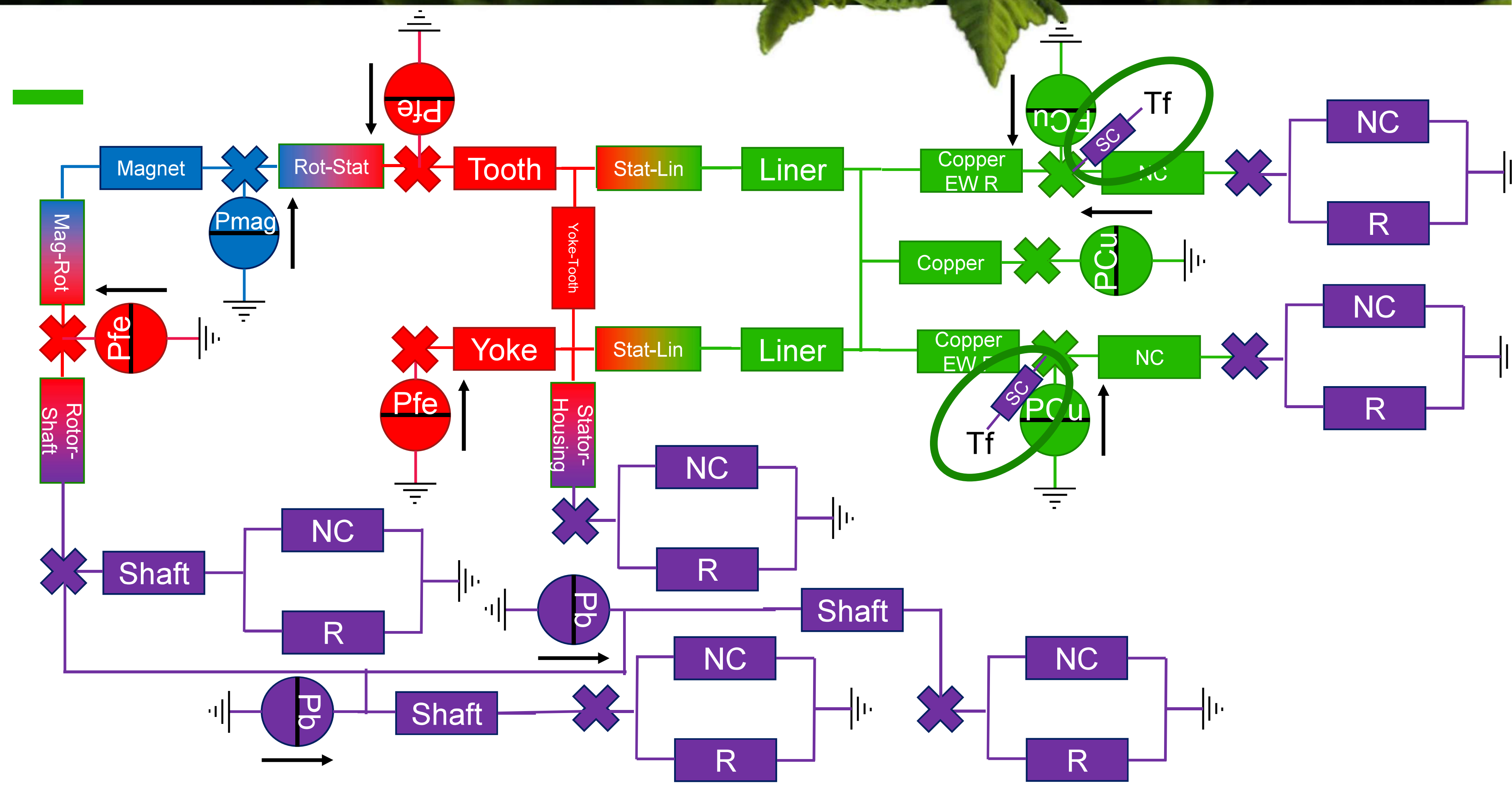


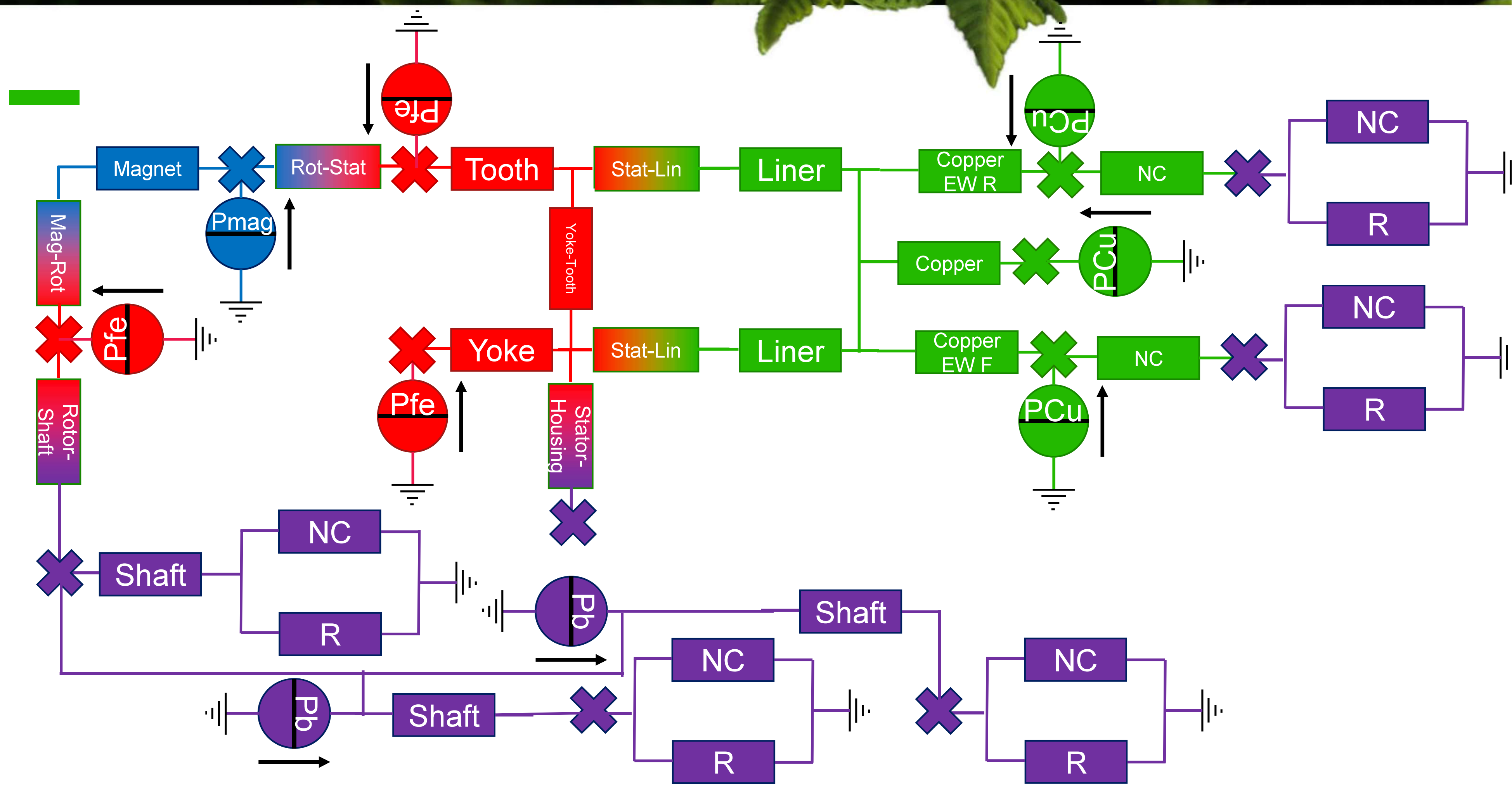
SPRAY COOLING

LUT University



DIRECT CONDUCTOR COOLING

LUT University



DIRECT CONDUCTOR COOLING