## E3SPreSSO

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Praliminay 20 T
Dipole Magnet Layout

## E3SPreSSO

Magnet Technology 2017, Ғ3 D~A A Fast Quench Protection System for HighAmsterdam, Netherlands

## The Promise of using HTS in Magnets

- $20 \mathrm{~T}+$ dipole magnets are within reach:
- Extreme current density possible: $1050 \mathrm{~A} / \mathrm{mm}^{2}$ in 20 T pp. magnetic field (Moore's Law Applies)
- Operation at higher temperatures: Helium gas (20K?)
- High transverse pressure resistance: $400 \mathrm{MPa}+$ (we need this)

Cable Specs for next Feather-M2.3-4 (this cable exists)

| strand no. | $77 \mathrm{~K} / \mathrm{SF}$ | Ic $4.2 \mathrm{~K} / 5 \mathrm{~T}$ | length (m) |
| ---: | :---: | :---: | :---: |
| 1 | 98 | 3050 | 29.2 |
| 2 | 98 | 3050 | 29.2 |
| 3 | 98 | 3050 | 27.1 |
| 4 | 81 | 3100 | 29.2 |
| 5 | 150 | 3097 | 27.4 |
| 6 | 140 | 3237 | 28.3 |
| 7 | 146 | 2304 | 25 |
| 8 | 210 | 2935 | 28 |
| 9 | 140 | 3237 | 28.3 |
| 10 | 123 | 2709 | 30 |
| 11 | 140 | 3237 | 28.3 |
| 12 | 140 | 3237 | 28.6 |
| 13 | 210 | 2935 | 28 |

700 A/ mm² Block Coil Cross-Section


Combined 39 kA @(4.2 K, 5 T, pp)
Estimated: 18 kA @(4.2 K, 20 T, pp)

## Fast Quench Protection

- With such high current densities and energies quench protection for accelerator sized magnets becomes a serious challenge ...
- CLIQ and Heaters can NOT work!
- Two options are to be considered:
- No protection. Rely on the stability of the coil.
- E3SPreSSO (this talk)
- External Energy Extraction Symbiotic Protection System for Series Operation
- What else? (a challenge for you perhaps?)



## How E³SPreSSO Works I



- The main coil is split up into N sections each protected by its own E3SPreSSO unit, which is connected in series
- The E3SPreSSO unit is:
- A near-zero self-inductance superconducting circuit that can be turned normal (superconducting switch).
- Located outside the main magnetic field:
- Robust and cheap Nb -Ti or $\mathrm{MgB}_{2}$
- Or with parallel resistor non-stabilized ReBCO tapes.
- Allows for protecting large- or string of HTS magnet(s) which previously did not exist yet



## How E³SPreSSO Works II



- Resistance is distributed: Energy Extraction is no longer limited by the insulation breakdown voltage
- Removes restriction on cable current -> Ramp-up still applies


# The design and numerical analysis of $\mathrm{E}^{3}$ SPreSSO requires some mathematics 

To help with the design
we created an excel
sheet that runs the
calculations (attached

here, feel free to use) | Microsoft Excel |
| :---: |
| Worksheet |

## Effective Material Properties

## - Properties from CryoComp

- Effective Material Properties
- Heat capacity: $C_{e f f}(T)$
- Thermal conductivity: $k_{e f f}(T)$
- Resistivity: $\rho_{e f f}(T)$
- Effective Properties for switch are indexed with s as:
- $C_{S}(T), k_{S}(T)$ and $\rho_{S}(T)$
- For the parallel resistor with p

$$
C_{e f f}(T)=\sum_{i=1}^{n_{m a t}} f_{i} C_{p i}(T)
$$

$$
k_{e f f}(T)=\sum_{i=1}^{n_{m a t}} f_{i} k_{i}(T)
$$

$$
\frac{1}{\rho_{e f f}(T)}=\sum_{i=1}^{n_{m a t}} \frac{f_{i}}{\rho_{i}(T)}
$$






## E3SPreSSO Unit Design Equations

- For the design we need to calculate:
- The length of the switch wire/ cable: $l_{s}$
- The length of the parallel resistor (if any): $l_{p}$
- The area of the parallel resistor: $A_{p}$
- Resistance of parallel resistor and switch 1

$$
R_{p}(T)=\frac{\rho_{p}(T) l_{p}}{A_{p}} \quad R_{s}(T)=\frac{\rho_{s}(T) l_{s}}{A_{s}}
$$

- Conservation of energy:

Magnetic energy in system must fit in heat capacity of switch

$$
C_{\text {ints }}=\int_{T_{0}}^{T_{\max }} C_{S}(T) d T
$$

$$
E_{s}=\frac{R_{p}\left(T^{*}\right)}{R_{s}\left(T^{*}\right)+R_{p}\left(T^{*}\right)} \frac{L I_{0}{ }^{2}}{2 N}=l_{s} A_{s} C_{i n t s}
$$

1

## Paralel Resistor



- Maximum voltage drop (Ohm's law):

$$
\frac{V_{\text {max }}}{I_{0}}=R_{E}=\frac{R_{S}\left(T^{*}\right) R_{p}\left(T^{*}\right)}{R_{S}\left(T^{*}\right)+R_{p}\left(T^{*}\right)}
$$

- T* is the "switching" temperature at which $V_{\max }$ should be effectively achieved. This choice will be numerically verified.


## Solving the Design Equations

- Solution is achieved in two steps
- Solving Equations 1,2 and 3 for $R_{p}\left(T^{*}\right)$ and $l_{s}$ yields:

$$
R_{p}\left(T^{*}\right)=\frac{-I_{0}^{2} L \rho_{s}\left(T^{*}\right) V_{\max }-A_{s} \sqrt{2 C_{\text {int }} I_{0} L N \rho_{S}\left(T^{*}\right) V_{\max }^{3}}}{-I_{0}^{3} L \rho_{S}\left(T^{*}\right)+2 A_{S}^{2} C_{\text {ints }} N V_{\max }}
$$

$$
l_{S}=\sqrt{\frac{I_{0} L V_{\max }}{2 N \rho_{\text {tape }}\left(T^{*}\right) C_{\text {ints }}}}
$$

$l_{s}$ Does not depend on $A_{s}$ meaning that $A_{s}$ can be traded off with $R_{p}\left(T^{*}\right)$

## - Exception Case:

- When $A_{s}$ is (too) large, the temperature no longer reaches
$T_{\max }$. A lower temperature design can still be achieved with:

$$
l_{S}=\frac{A_{S} V_{\max }}{I_{0} \rho_{S}\left(T^{*}\right)} \quad R_{p}=\infty
$$

- Do not use->
- Conservation of energy for the parallel resistor is given as

$$
E_{p}=\frac{R_{S}\left(T^{*}\right)}{R_{S}\left(T^{*}\right)+R_{p}\left(T^{*}\right)} \frac{L I^{2}}{2 N}=l_{p} A_{p} C_{\text {intp }}
$$

- Which solves for $l_{p}$ and $A_{p}$ as

$$
C_{\text {intp }}=\int_{T_{0}}^{T_{\max }} C_{p}(T) d T
$$

$$
A_{p}=\sqrt{\frac{E_{p} \rho_{p}\left(T^{*}\right)}{C_{\text {intp }} R_{p}}} \quad l_{p}=\sqrt{\frac{E_{p} R_{p}\left(T^{*}\right)}{C_{\text {intp }} R_{p}}}
$$

## 20T Prototype Magnet Nb-Ti Switch (the original idea)

- Assuming our preliminary HTS 20T+ prototype design 900A/ mm²
- Assuming 8 E3SPReSSO units with Nb-Ti cable and no parallel resistor
- The magnet:
- $\mathrm{B}_{\mathrm{op}}=20 \mathrm{~T}$,
- $\mathrm{I}_{\mathrm{op}}=12000 \mathrm{~A}$
- $\mathrm{L}=0.042 \mathrm{H}(3 \mathrm{MJ})$
- $\mathrm{T}_{\mathrm{op}}=4.5 \mathrm{~K}$
- 66\% hastelloy, 1.3\% silver, 26\% copper, 0.7\% YBCO
- E3SPreSSO:
- $\mathrm{N}=8$,
- $\mathrm{V}_{\max }=1000 \mathrm{~V}$
- $\mathrm{T}_{\max }=250 \mathrm{~K}$
- $\mathrm{T}^{*}=20 \mathrm{~K}$
- $50 \% \mathrm{Cu}, 50 \% \mathrm{Nb}-\mathrm{Ti}$
- $\mathrm{A}_{\mathrm{s}}=22 \mathrm{~mm}^{2}$
- Result:
- $l_{s}>5000 m$ per unit
- NOT GOOD!


## 20T Prototype Magnet HTS Switch (evolution)

- Assuming our preliminary HTS 20T+ prototype design 900A/ mm²
- Assuming 8 E3SPReSSO units with non-stabilized HTS switch stainless steel parallel resistor

- The magnet:
- Bop = 20 T ,
- Iop = 12000 A
- $\mathrm{L}=0.042 \mathrm{H}(3 \mathrm{MJ})$
- Top $=20 \mathrm{~K}$
- 66\% hastelloy, 1.3\% silver, 26\% copper, 0.7\% YBCO
- E3SPreSSO:
- $\mathrm{N}=8, \mathrm{Vmax}=1000 \mathrm{~V}$
- $\operatorname{Tmax}=250 \mathrm{~K}$
- $\mathrm{T}^{*}=135 \mathrm{~K}$
- 90\% hastelloy, 1.8\% silver, 0.9\% YBCO
- As $=15 \mathrm{~mm}^{2}$
- Result:
- $l_{s}=16.7 \mathrm{~m}$
- $A_{p}=55.5 \mathrm{~mm}^{2}$
- $l_{p}=11 \mathrm{~m}$


## Numerical Model

- Solving current in ICED ring 1 and E3SPreSSO

$$
\begin{aligned}
& \frac{d I_{E}}{d t}=\frac{L_{r} R_{E} I_{E}}{-M_{r}^{2}+L_{r} L}-\frac{M_{r} R_{r} I_{r}}{-M_{r}^{2}+L_{r} L}, \\
& \frac{d I_{r}}{d t}=\frac{L R_{E} I_{E}}{-M_{r}^{2}+L_{r} L}+\frac{M_{r} R_{r} I_{r}}{-M_{r}^{2}+L_{r} L},
\end{aligned}
$$

Feather-M2 Magnet


- Solving temperatures
- Temperature in parallel resistor,

ICED ring,
switch
and main coil

$$
\frac{d T_{p}}{d t}=\frac{\rho_{p}\left(T_{p}\right) I_{p}^{2}}{A_{p}^{2} C_{p}\left(T_{p}\right)}, \quad \frac{d T_{r}}{d t}=\frac{\rho_{r}\left(T_{r}\right) I_{r}^{2}}{A_{r}^{2} C_{r}\left(T_{r}\right)}, \quad \frac{d T_{s}}{d t}=\frac{\rho_{s}\left(T_{s}\right) I_{s}^{2}}{A_{s}^{2} C_{s}\left(T_{s}\right)}, \quad \frac{d T_{m}}{d t}=\frac{\rho_{m}\left(T_{m}\right) I_{m}^{2}}{A_{m}^{2} C_{m}\left(T_{m}\right)},
$$

## Numerical Analysis

- The numerical model is evaluated on the 20T magnet prototype
- The switch is activated after detection and delay time (see eq.)
- After the switch is activated most of the current is diverted to the parallel resistor
- Temperature of both switch and parailel resistor reach requested 200K
- ICED works as expected picking up half of the current in the main coil (about 40\% of energy)
- Coil peak temperature is a comfortable 240K
- Energy absorbtion:




## Numerical Analysis Cases

TABLE II
USED FRACTION OF MATERIAL USED FOR THE CONDUCTOR OF THE MAIN COIL AND FOR THE DIFFERENT OPTIONS FOR THE SWITCH．AS WELL AS THE assumed values for the operating temperature and relevant temperatures．

| Case | Nb －Ti | $\mathrm{MgB}_{2}$ | ReBCO | Cu RRR20 | $\begin{aligned} & \hline \hline \mathrm{Cu} \\ & \mathrm{RRR} 100 \end{aligned}$ | $\begin{aligned} & \hline \hline \mathrm{Ag} \\ & 99 \% \end{aligned}$ | $\begin{aligned} & \hline \hline \text { StSt } \\ & 304 \end{aligned}$ | $\begin{aligned} & \hline \mathrm{Cu}-\mathrm{Ni} \\ & 70-30 \end{aligned}$ | $\begin{aligned} & \hline \mathrm{Cu}-\mathrm{Zn} \\ & 90-10 \end{aligned}$ | other | $\begin{aligned} & \hline A_{m} / A_{s} \\ & {\left[\mathrm{~mm}^{2}\right]} \end{aligned}$ | $\begin{aligned} & \hline \hline T_{\mathrm{op}} \\ & {[\mathrm{~K}]} \end{aligned}$ | $\begin{aligned} & \hline T_{\mathrm{cs}} \\ & {[\mathrm{~K}]} \end{aligned}$ | $\begin{aligned} & \hline \hline T_{t} \\ & {[\mathrm{~K}]} \end{aligned}$ | $\begin{aligned} & \hline \hline T_{c} \\ & {[\mathrm{~K}]} \end{aligned}$ | $\begin{aligned} & \hline \hline T^{*} \\ & {[\mathrm{~K}]} \end{aligned}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1 | 80\％ |  |  | － | 20\％ | － | － | － | － | － | 15 | 4.5 | 7.0 | 8.5 | 10 | 50 |
| 2 | 94．5\％丁 ヤГ |  |  | － | 5．5\％ | － |  |  |  | Poisoned Copoer |  |  |  |  | 10 | 50 |
| 3 | 49\％ | －1 |  | － | － | － |  |  |  | 8.5 8.5 | 10 | 50 |
| 4 | 30\％ | － | － | － | － | － | ， |  |  | － | 15 | 4.5 | 7.0 | 8.5 | 10 | 50 |
| 5 | TएГS ${ }^{1.6 \%}$ |  | － | － | － | － | － | 54．4\％ | － |  |  |  |  | － | 15 | 20 | 30 | 35 | 40 | 100 |
| 6 |  |  | 0．91\％ | － | － | － | 90．9\％ | ． | － | 8．1\％ | 6.6 | 20 | 50 | 71.5 | 93 | 100 |
| 7 | H1卩 |  | 0．91\％ | － | － | 1．8\％ | 90．9\％ | － | － | 6．3\％ | 6.6 | 20 | 50 | 71.5 | 93 | 100 |
| coil | － | － | 0．66\％ | 26．6\％ | － | 1．33\％ | 66．6\％ | － | － | 4．6\％ | 13.3 | 20 | 40 | 62.5 | 85 | － |
| parR | － | － | － | － | － | － | 100\％ | － | － | － | － | ＊ | － | － | － | － |
| ring | － | － | － | 100\％ | － | － | － | － | － | － | － | 20 | － | － | － | － |

＊Same operating temperature as the switch．
－Performed numerical analysis on different cases with both
－LTS switch materials at operating temperature of 4．5K
－HTS switch materials at operating temperature of 20K
－Also added Inductively Coupled Energy Extraction （ICED quench－back）loops

## Numerical Analysis Results

## TABLE III

CALCULATED VALUES FOR THE DESIGN VARIABLES AS WELL AS THE RESULTS OF THE ANALYTICAL AND NUMERICAL ANALYSIS OF THE DESIGNS.

| Case | Design |  |  |  |  | conductor properties |  |  |  |  | final temperatures |  |  |  | energy distribution |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | $\begin{aligned} & \ell_{s} \\ & {[\mathrm{~m}]} \end{aligned}$ | $\begin{aligned} & R_{p}\left(T^{*}\right) \\ & {[\mathrm{m} \Omega]} \end{aligned}$ | $\begin{aligned} & R_{E}\left(T^{*}\right) \\ & {[\mathrm{m} \Omega]} \end{aligned}$ | $\begin{aligned} & \ell_{p} \\ & {[\mathrm{~m}]} \end{aligned}$ | $\begin{aligned} & A_{p} \\ & {\left[\mathrm{~mm}^{2}\right]} \end{aligned}$ | $\ell_{\mathrm{mpz}}$ <br> [ $\mu \mathrm{m}$ ] | $\begin{aligned} & E_{\mathrm{MQE}} \dagger \\ & {[\mu \mathrm{~J}]} \end{aligned}$ | $V_{\text {nzp }}$ $[\mathrm{m} / \mathrm{s}]$ | $\begin{aligned} & E_{s a, T \mathrm{cs}} \\ & {[\mathrm{~mJ}]} \end{aligned}$ | $\begin{aligned} & E_{s a, T \mathrm{t}} \\ & {[\mathrm{~mJ}]} \end{aligned}$ | $T_{m}$ <br> [K] | $\begin{aligned} & T_{s} \\ & {[\mathrm{~K}]} \end{aligned}$ | $T_{p}$ <br> [K] | $\begin{aligned} & T_{r} \\ & {[\mathrm{~K}]} \end{aligned}$ | $\begin{aligned} & E_{s} \\ & {[\%]} \end{aligned}$ | $E_{p}$ <br> [\%] | $E_{r}$ <br> [\%] |
| 1 | 375 | $m$ | 84 | n.a. | n.a. | 2000 | 1000 | 13.5 | 121 | 195 | 355 | 59.8 | 168 | 192 | 64 | 0 | 36 |
| 2 |  |  | 84 | n.a. | n.a. | 550 | 320 | 12.05 | 11.9 | 19.0 | 243 | 168 | 222 | 226 | 53 | 0 | 47 |
| 3 |  |  | 84 | n.a. | n.a. | 44 | 20 | 22.0 | 7.3 | 11.8 | 224 | 185 | 197 | 199 | 61 | 0 | 39 |
| 4 | צ.0 | $1 \angle 2$ | 263 | 8.67 | 35 | 8 | 4.6 | 29.9 | 3.2 | 5.0 | 239 | 201 | 190 | 193 | 22 | 41 | 37 |
| 5 |  |  | 317 | 8.67 | 38 | 16 | 960 | 0.63 | 255 | 485 | 240 | 201 | 191 | 195 | 18 | 45 | 37 |
| 6 |  |  | 771 | 8.67 | 45 | 19 | 3980 | 0.41 | 552 | 1617 | 238 | 209 | 192 | 195 | 8 | 55 | 37 |
| 7 |  |  | 457 | 8.67 | 41.7 | 64 | 13500 | 0.27 | 947 | 2762 | 242 | 208 | 192 | 196 | 13 | 50 | 37 |
| coil | - | - | - | - | - | 1480 | $4.4 \cdot 10^{5}$ | 0.19 | $7.1 \cdot 10^{7}$ | $1.4 \cdot 10^{8}$ | - | - | - | - | - | - | - |

$\dagger$ MQE is defined in the multi-strand regime of the cable [22].

- LTS Pure copper matrix - results in very long cables. Also slow switching due to strong temperature dependence of resistivity.
- LTS Poisoned copper matrix - very low quench energies contact with liquid helium recommended to increase stability
- HTS non-stabilized - very high switching energy and low propagation velocity cause it difficult to switch to normal despite absence of stabilizer.
- For HTS switch (case 6) most of the energy is dumped in the parallel resistor

Energy Distribution


- The GOOD:
- The E3SPreSSO provides a method for extracting energy for (string of) HTS magnets of any size which did not exist yet
- The E3SPreSSO can ramp-down faster than other systems by distributing its effective voltage over the circuit
- The BAD:
- For timely energy extraction for high current density coil 900A/ mm² many units are needed for case study 8 per meter coil
- Need extra joints to connect all the units
- Need quench heaters or CLIQ for all units
- Considering stability, to make this work reliably is going to be a serious challenge
- Only use $E^{3}$ SPreSSO if there is no alternatives
- Hopefully quenches in HTS can be timely detected also for higher current densities
- to be continued with Feather-M2.3-4


## - Final Conclusion




Feather-M2 Rendering

## Thank You for your attention

