An electric-circuit model of inter-tape contact resistance and current sharing for REBCO cable

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Main driving questions

- What is an appropriate model to provide the insight on the impact of contact resistance in REBCO cables?
- What is the optimal contact resistance R_c for REBCO cables to address the needs between current sharing and to suppress excessive Eddy currents?
  - Would current sharing benefit the cable performance in the presence of a localized defect?
- What is the impact of having I_c and n-value variations on the performance of different REBCO cable configurations?

Outline

1) **Introduction of the n-Stacked-Tape Cable model**
2) **Validation of the model**
3) **Applications**

   - Simulations and measurements of a localized defect and current sharing in stacked-tape cable

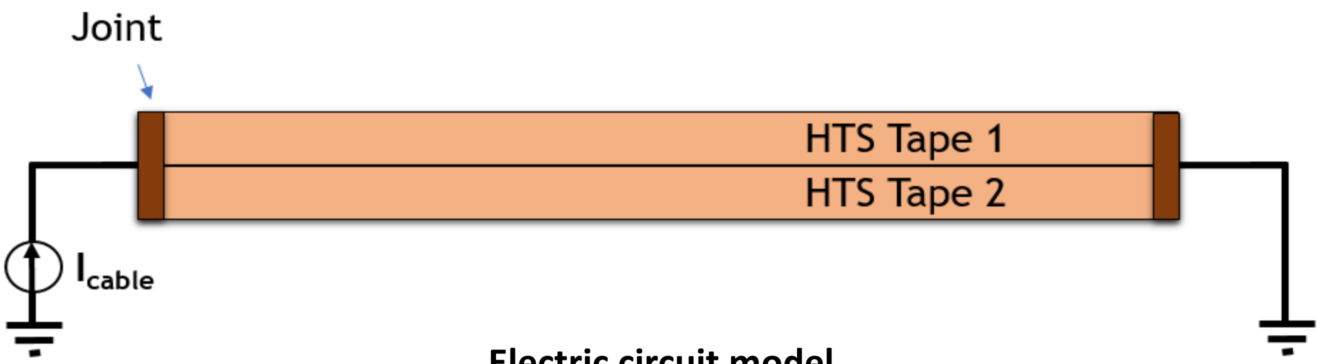
   - Monte Carlo simulations of I_c and n value variations in n-Stacked-Tape Cable

4) **Conclusions and next steps**

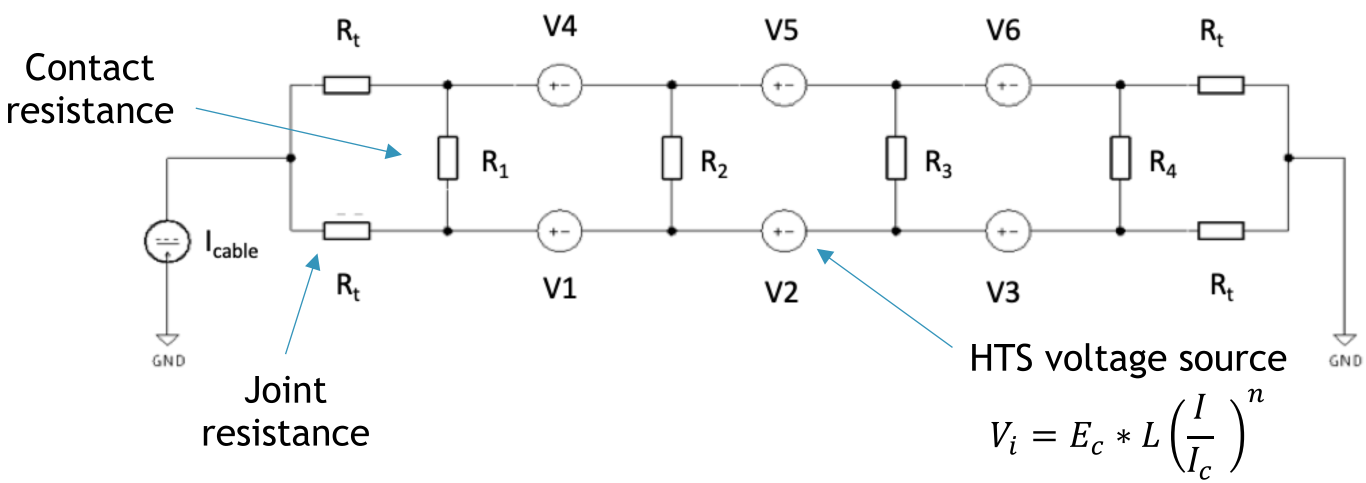
Stacked-tape case

We developed a simple electric-circuit model based on Ngspice to study the impact of contact resistance on stacked-tape cable

Diagram of 2 tapes – the simplest case



Electric circuit model

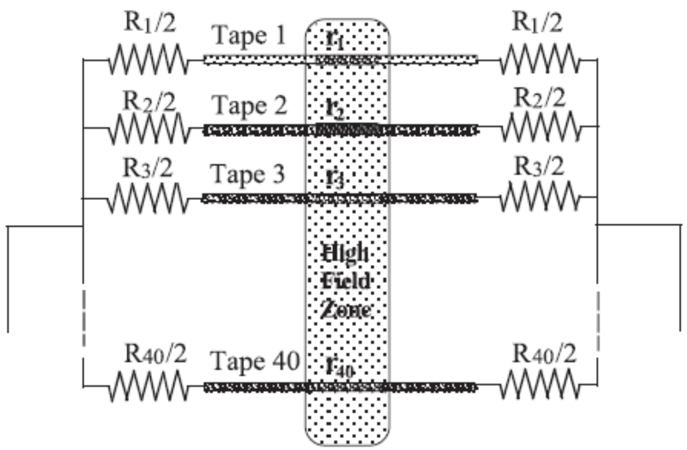


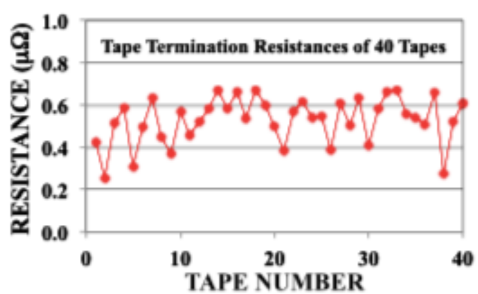
*Impact of magnetic field on the I_c not considered

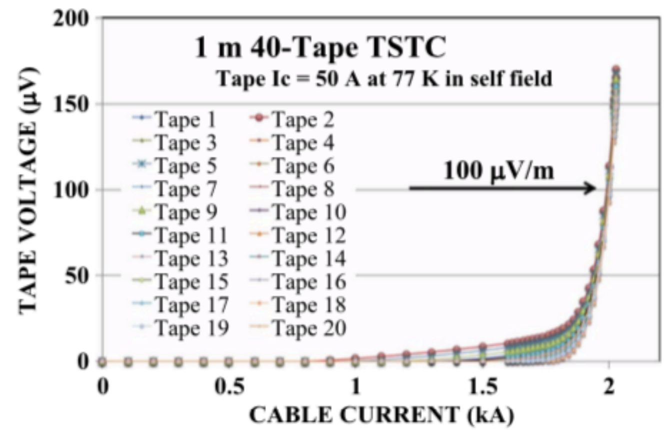
Validation of the model

We reproduce the published results as a first validation to the model

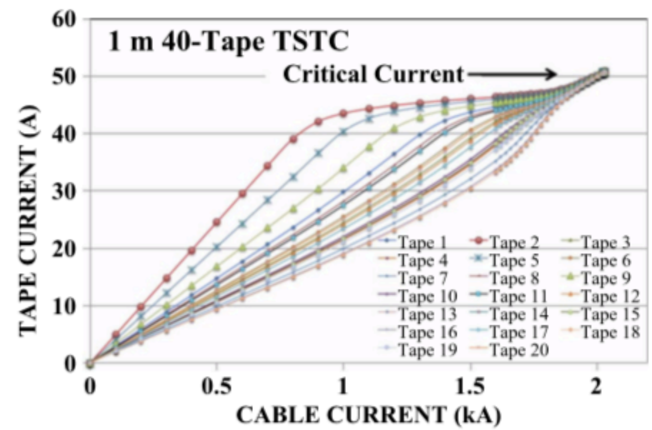
1 m 40-tape TSTC cable at 77 K in self-field







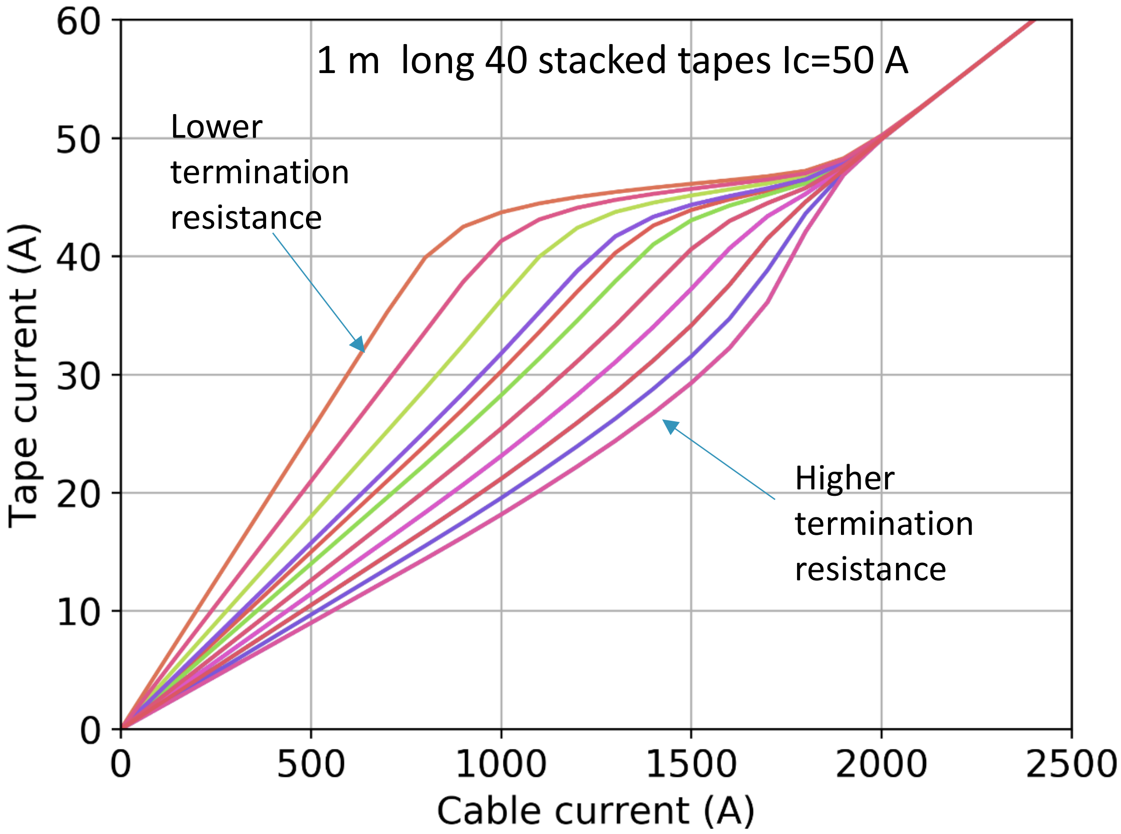
(a)



(b)

Takayasu *et al.,* IEEE TAS 2016
DOI 10.1109/TASC.2010.2094176

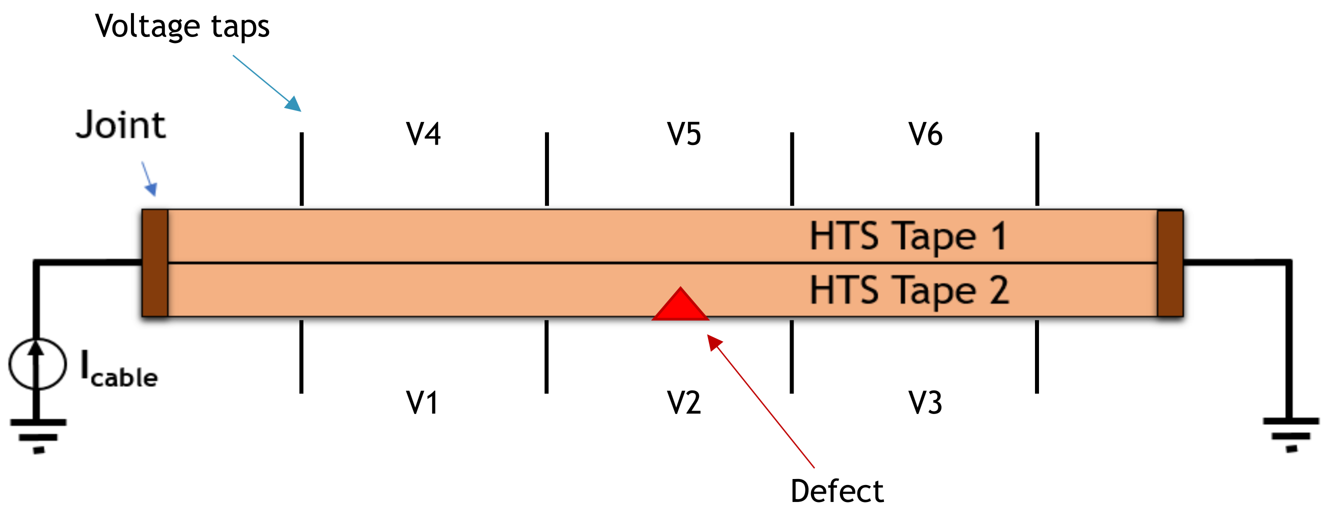
Our model reproduced the current distribution

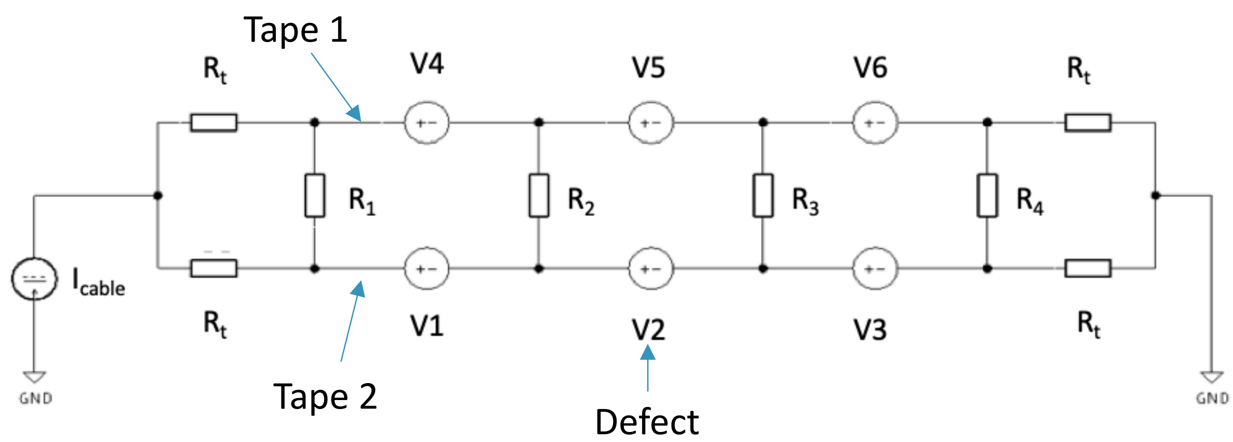


- Tapes with lower termination resistance carry a higher amount of current until the cable critical current is reached

Simulations and measurements of a localized defect in stacked-tape cable

We studied the impact of a localized defect in the 2-tape cable with two cases: tapes isolated and soldered

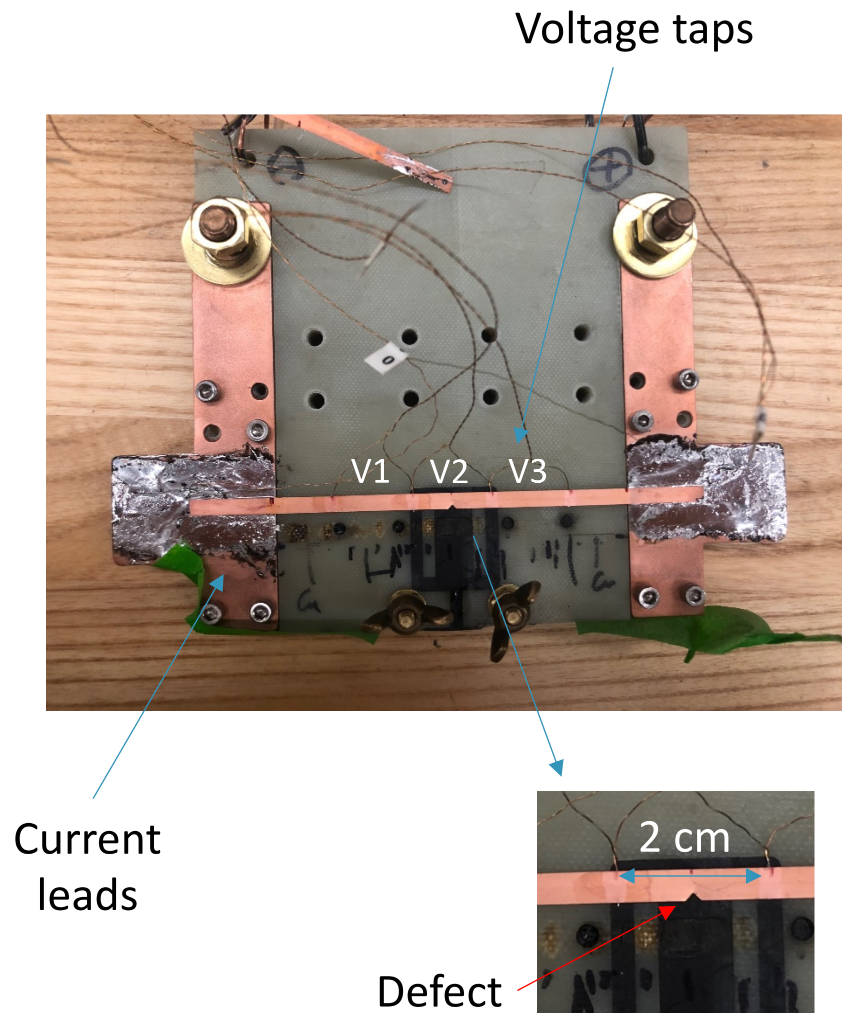




We tested both cases with SuperPower 4 mm wide tapes at 77 K, self-field

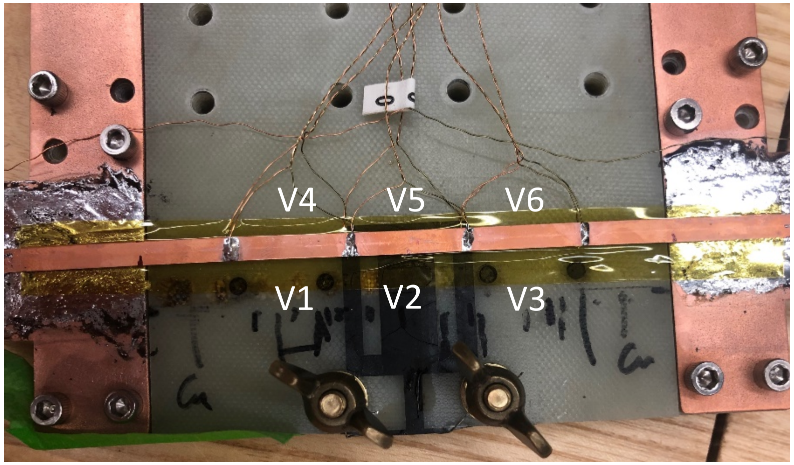
- Three voltage sections, each 2 cm long
- A defect in the center section of tape 2
- Data from the measured I_c/n at self-field were used in calculations

Section	I_c (A)	n
V1	132.3	30.5
V2	89.4	24.2
V3	133.1	31.0
V4	133.1	28.9
V5	130.7	30.7
V6	131.8	29.7



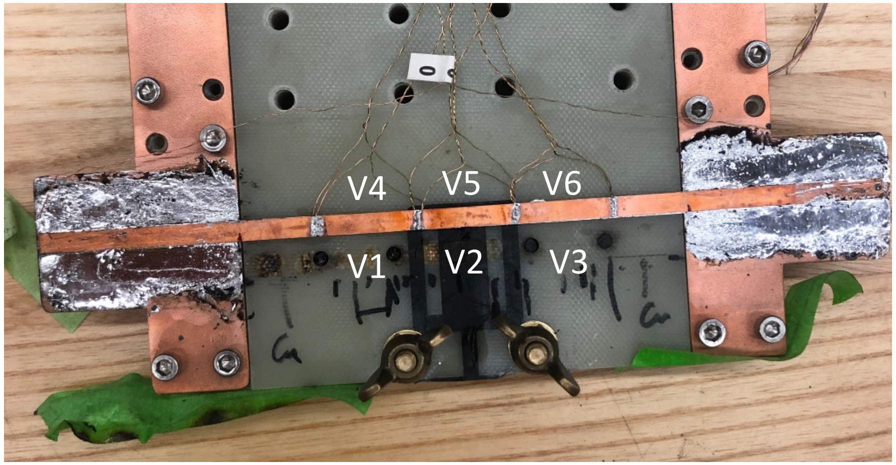
We performed two types of I_c tests on the 2-stack of tapes: insulation and solder between tapes.

Tapes isolated with Kapton tape



R_c = 1000 Ω used for the insulated case

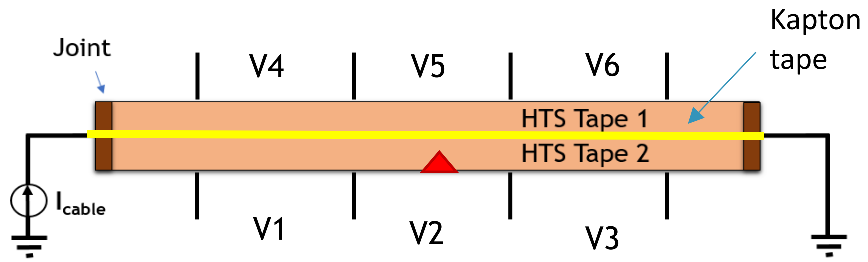
Tapes soldered with $Pb_{40}Sn_{60}$ solder

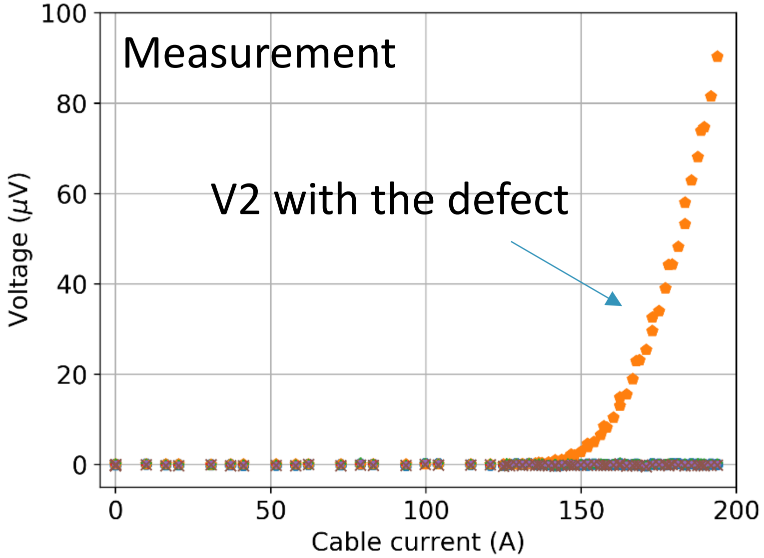


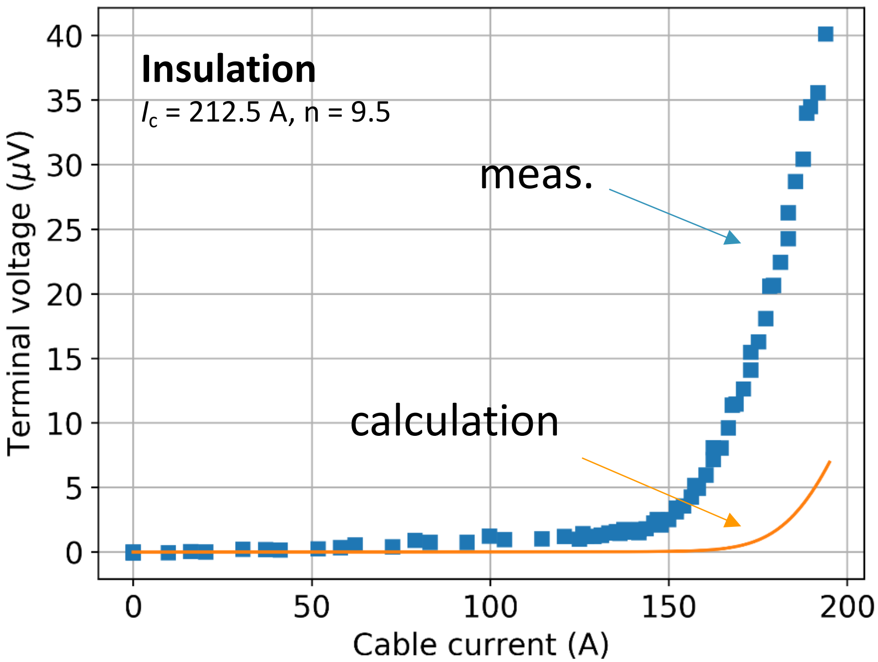
R_c = 46 nΩ* used for the soldered case

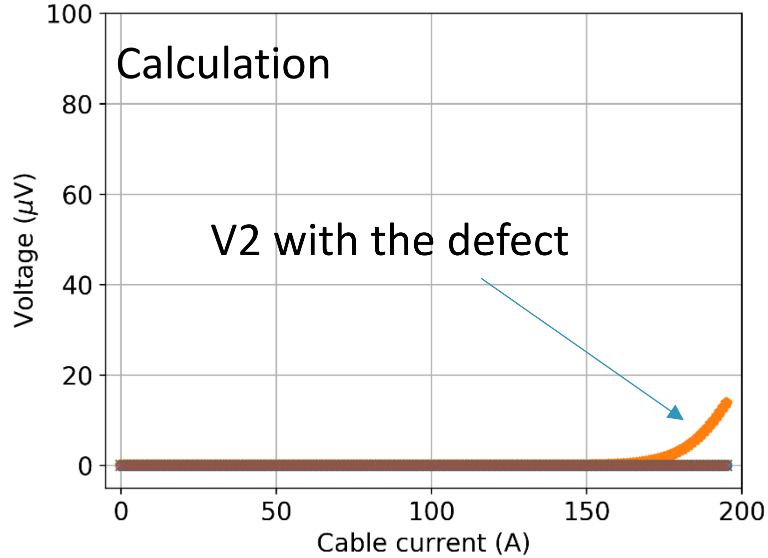
*Solder conductivity 0.27×10^8 S/m at 77 K
Yeekin Tsui *et al* 2016, *SST* **29** 075005

Simulations qualitatively agree with measurements: insulated case



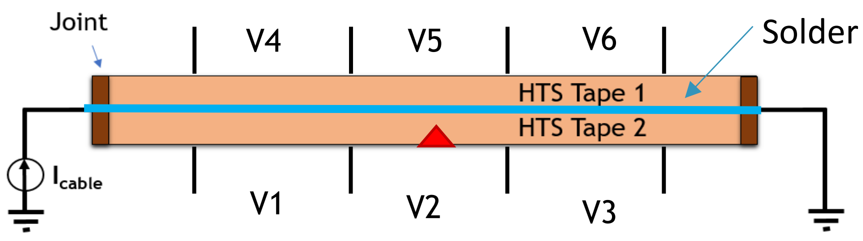


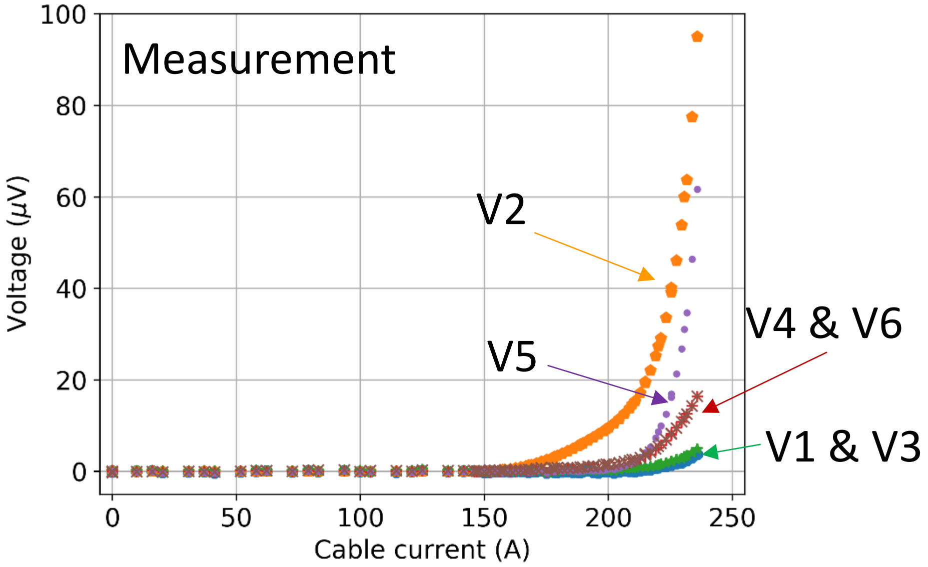


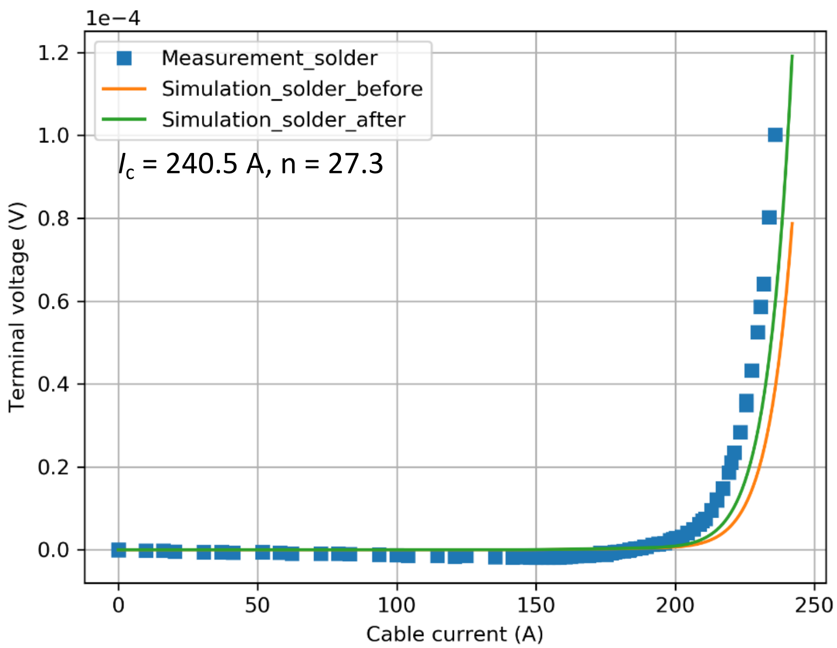


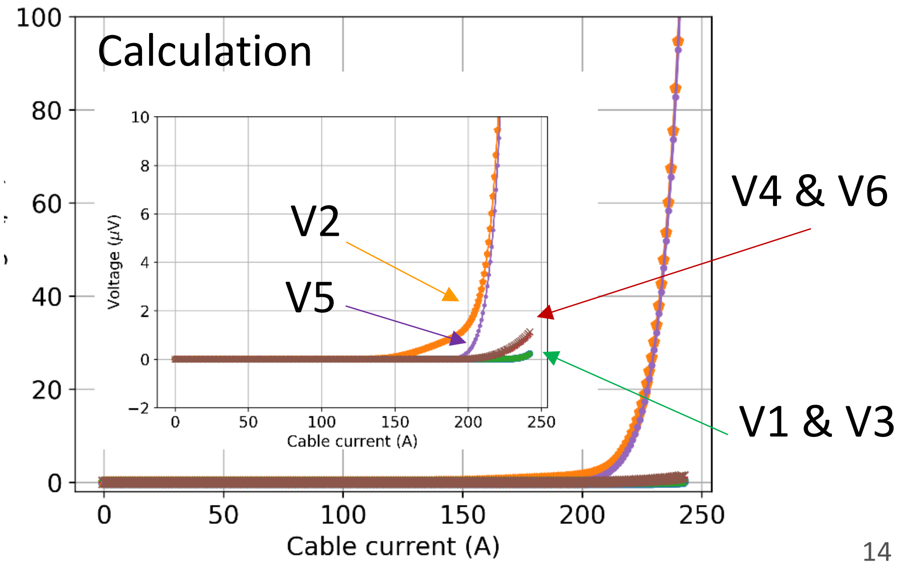
- Self-field impact on tape I_c not considered

Simulations qualitatively agree with measurements: soldered case









The voltage rise observed for the soldered case was not due to the potential degradation in the sections during soldering

- We un-soldered the tapes and measured I_c and n-value for each tape separately to verify if degradation of the tapes has occurred
- I_c degradation < 3%. Negligible change on n value

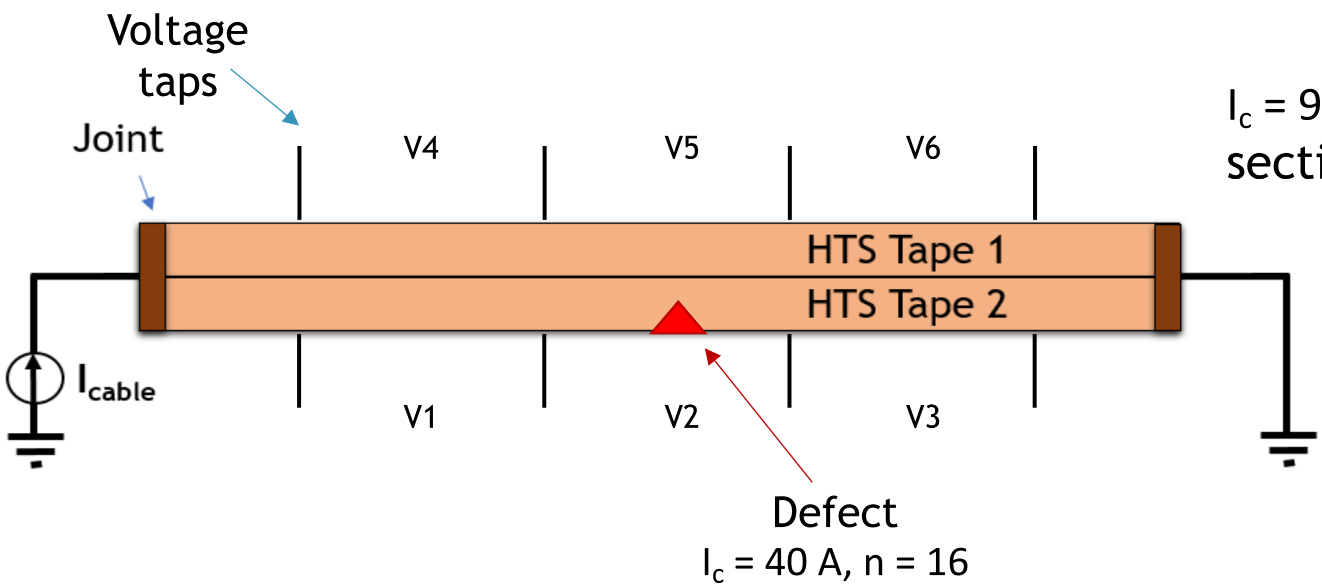
Defect section → V2

HTS section	I_c (A)		n	
	Before	After	Before	After
V1	132.3	*	30.5	*
V2	89.4	86.7	24.2	24.4
V3	133.1	*	31.0	*
V4	133.1	130.4	28.9	28.8
V5	130.7	129.9	30.7	29.9
V6	131.8	129.2	29.7	28.3

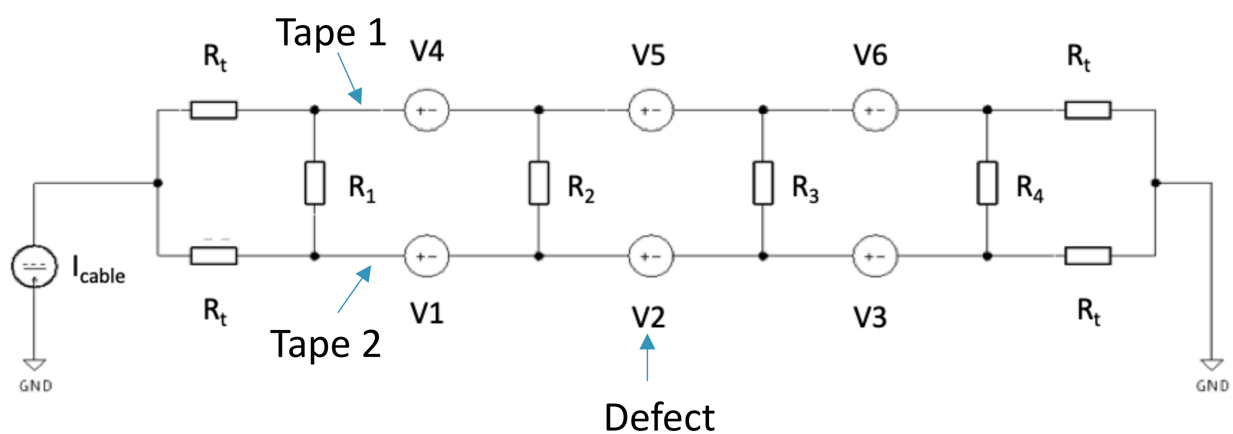
* Values that could not be measured after

With the validated model, we can now shed light on how the contact resistance affect the current bypassing the defect

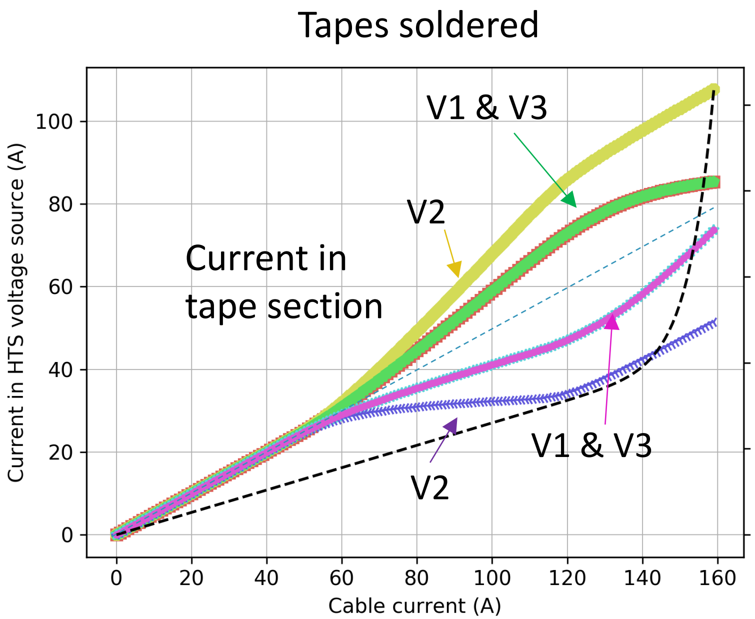
Reminder on the model

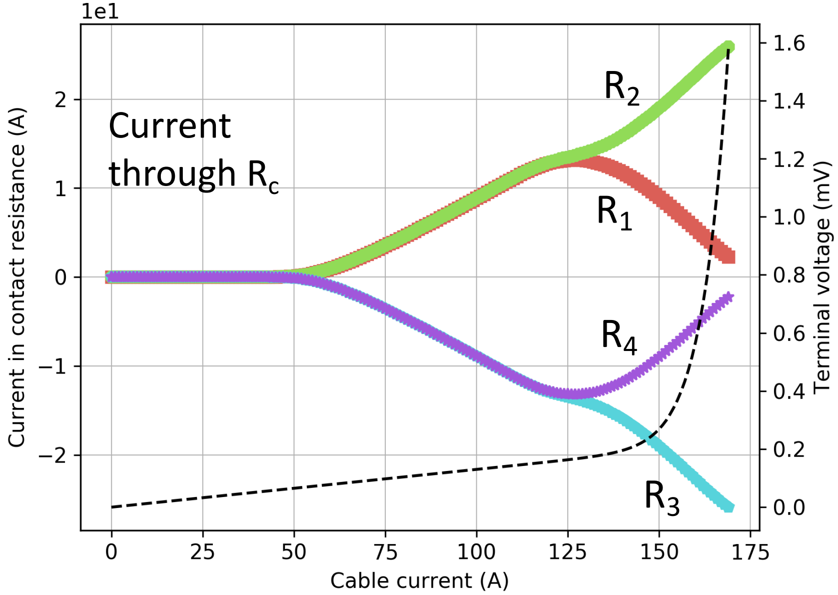


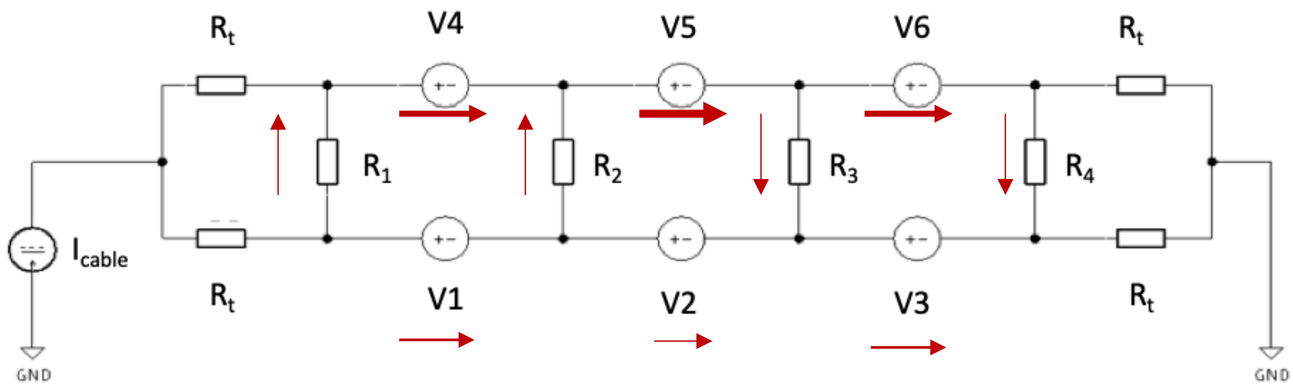
I_c = 95 A, n = 32 in all sections except for V2



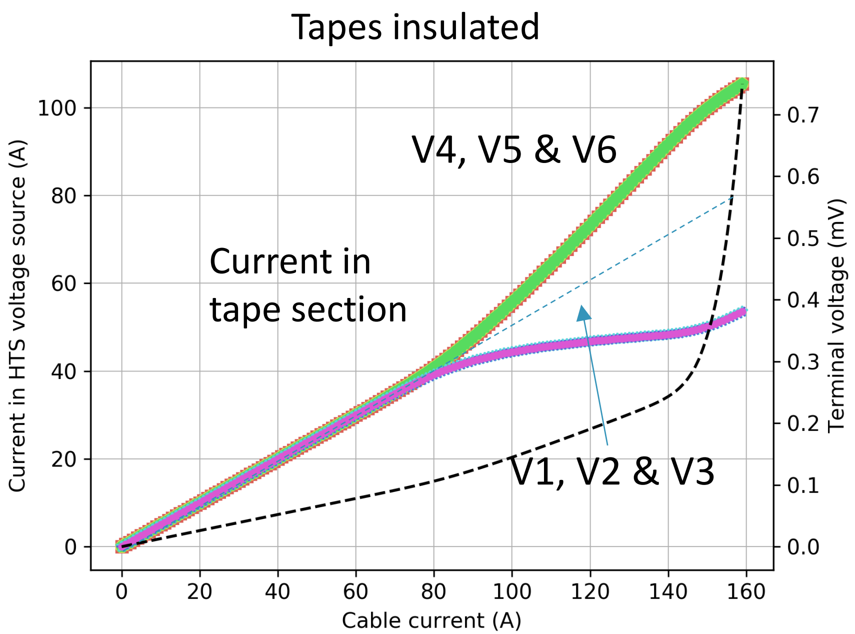
Low contact resistance allows current to bypass the damaged section when approaching its critical current.

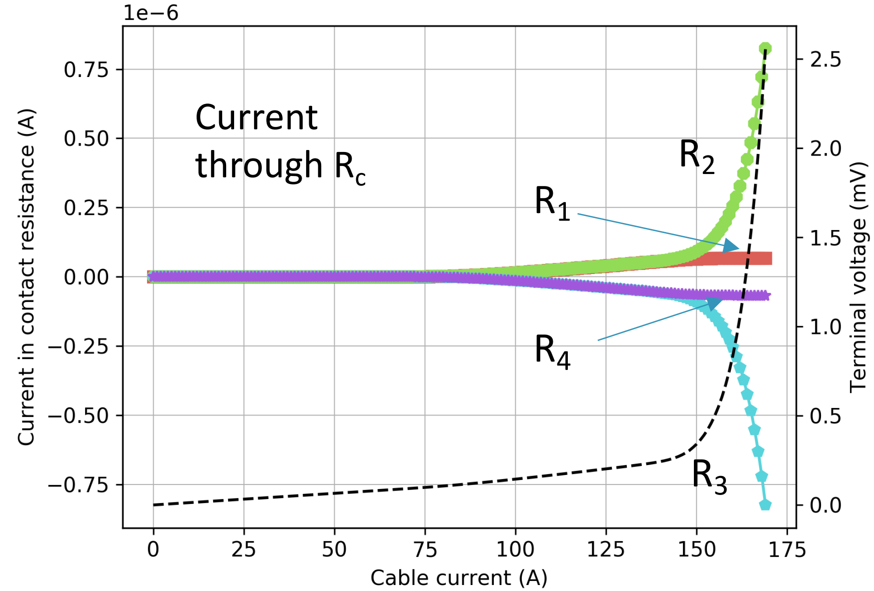


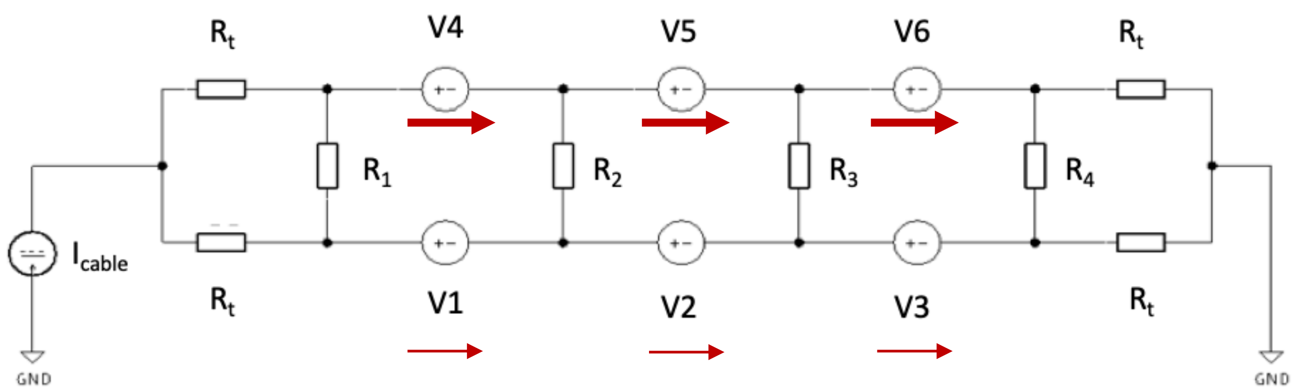




In the case of high contact resistance current sharing is determine by the terminal resistances

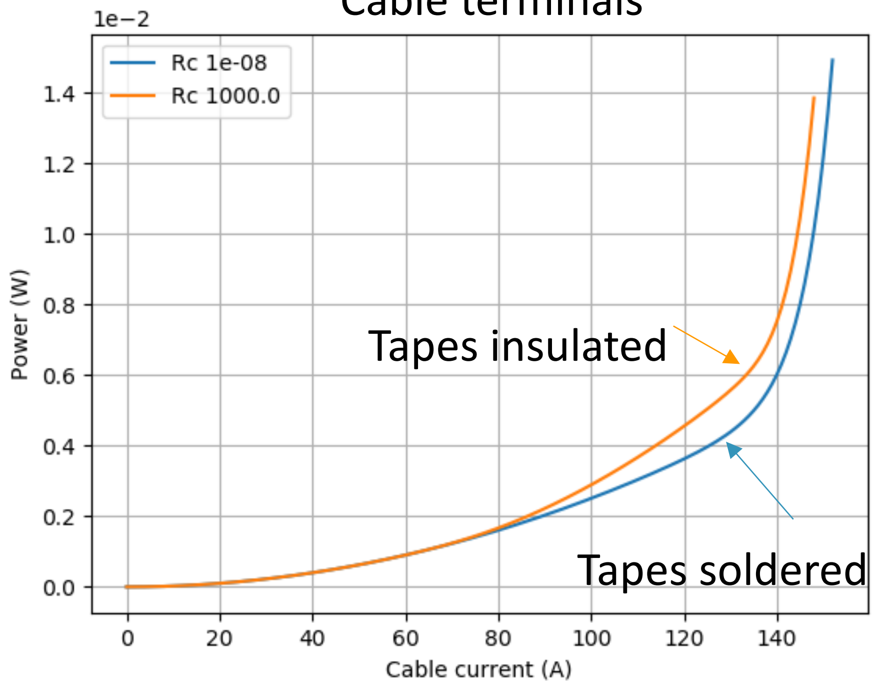




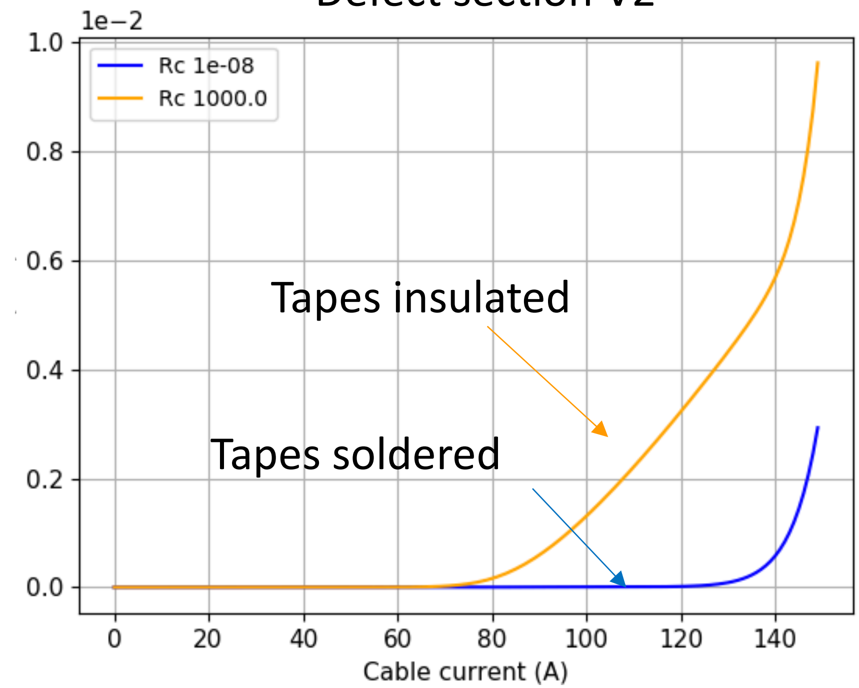


Low contact resistance reduces the heat generation

Cable terminals

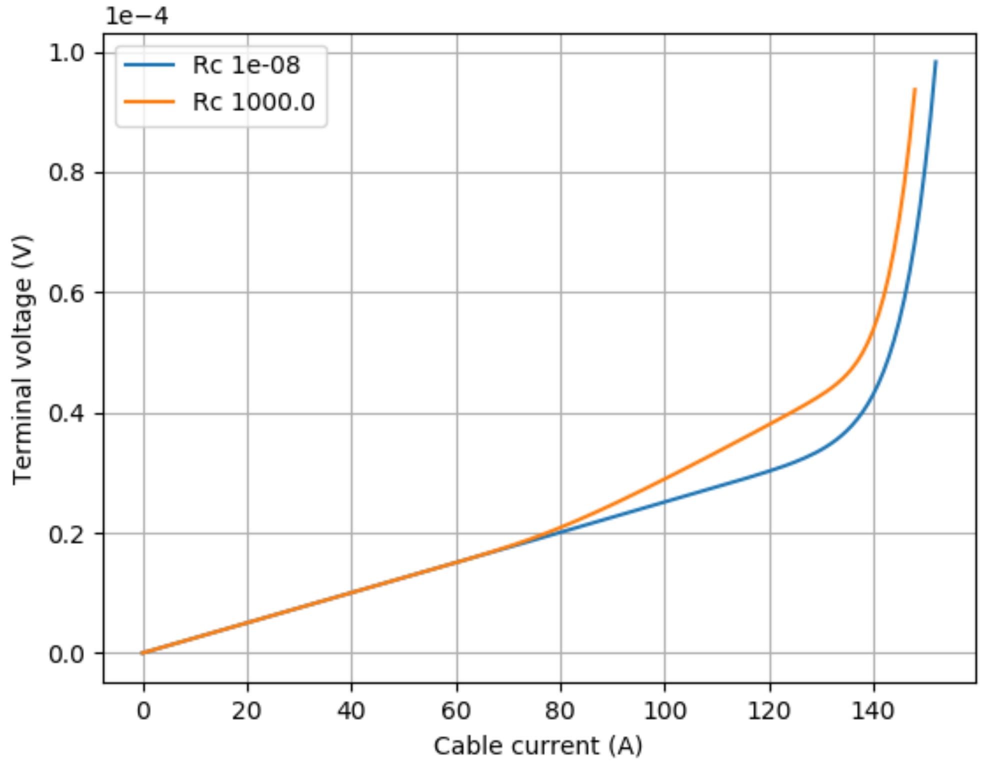


Defect section V2



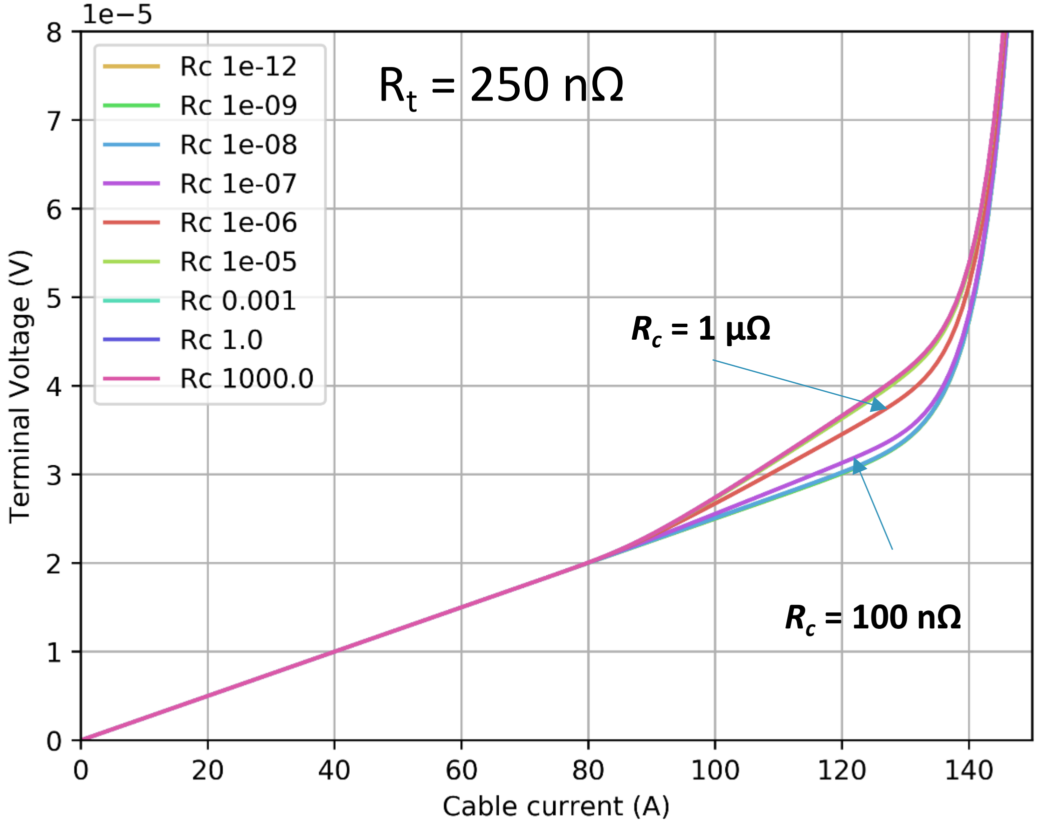
- We need to reduce contact resistance to reduce the temperature rise during transition

Cable I_c is increased 2% when the contact resistance is 10 nΩ



- **Rc = 10 nΩ**
  - I_c = 150.1 A, n = 32.5, Fit-error = 2.299x10^{-7} V
- **Rc = 1000 Ω**
  - I_c = 148.1 A, n = 22.9, Fit-error = 2.40016x10^{-5} V

We can estimate the threshold value for the R_c to achieve good contact



Optimal R_c depends on termination resistance.

Rt	Good contact (Ω)
25 μΩ	≤ 10 μ
250 nΩ	≤ 100 n
2.5 nΩ	≤ 1 n

tape 1= 100 A; tape 2=50 A. n = 30

Monte Carlo simulations of I_c and *n*-value variations in the stacked-tape cable

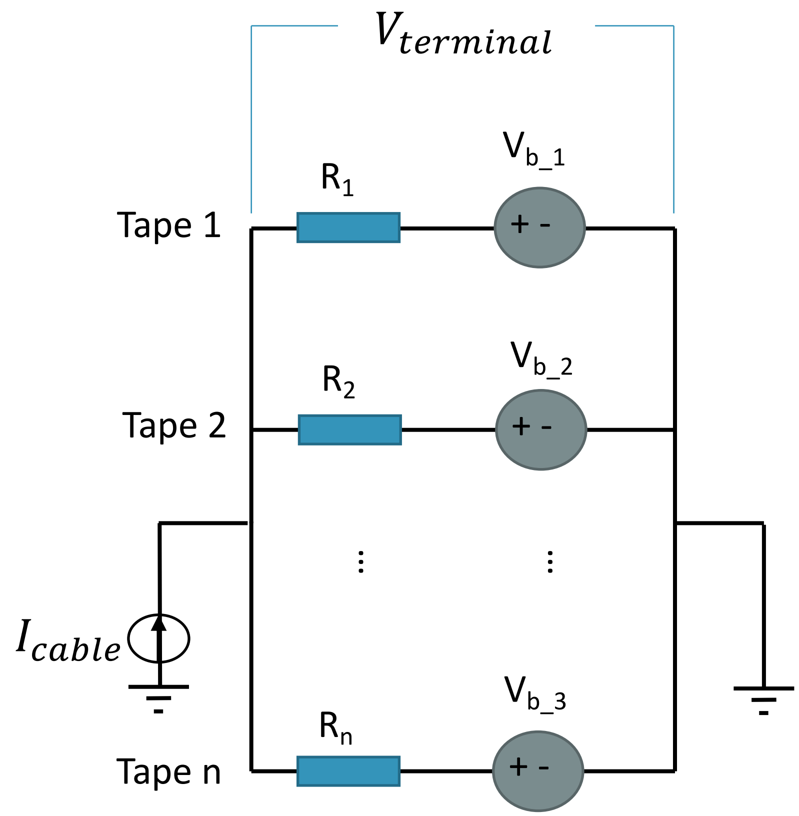
We performed Monte Carlo simulations to study the impact variations in I_c and n-value on the cable performance

- We used the power law to model the voltage in the superconducting tapes

$$V_{b\_i} = E_c * L\left(\frac{I}{I_c}\right)^n$$

$$V_{terminal} = V_{b\_i} + \frac{R_i}{n} * I_{cable}$$

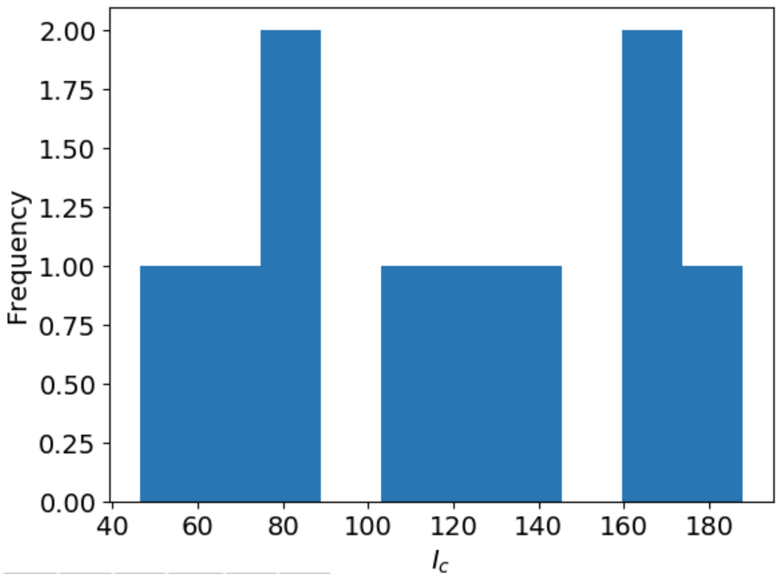
- E_c = 100 µV/m
- L = 1 m
- R_i = 500 nΩ



*Pothavajhala *et al.*, IEEE TAS 2015, 2371923
I_c and n-value variations along the tape length

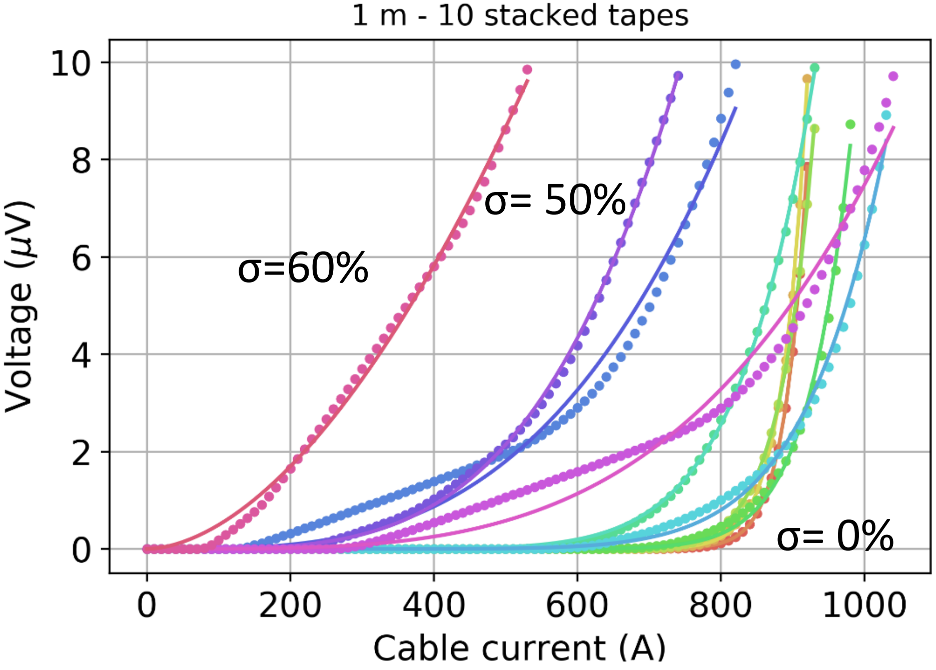
We calculated the terminal V(I) transitions with different standard deviations of the normal distribution of I_c and n-value with population size of 500

I_c distribution for σ = 50%



Mean values:
I_c = 100 A
n-value = 30

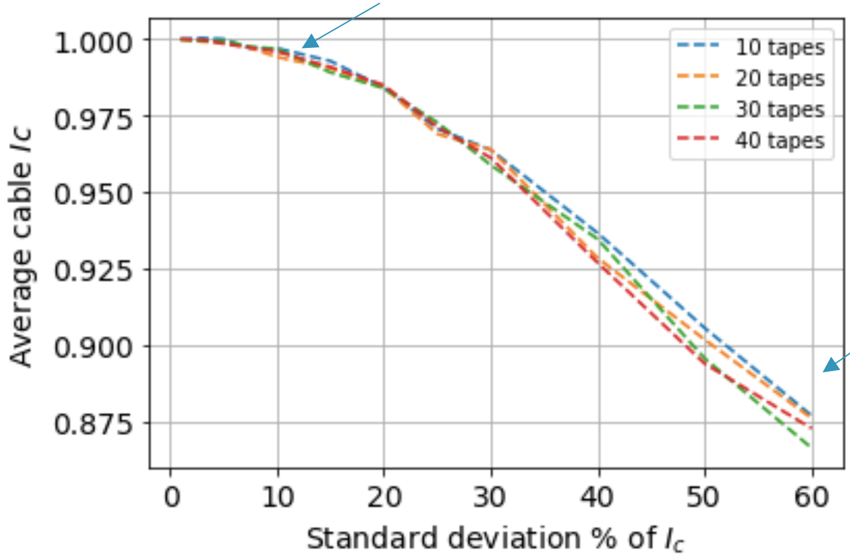
Example V(I) for different σ in Ic



$$V_{b\_i} = V_{terminal} - \frac{R_t}{n} * I_{cable}$$

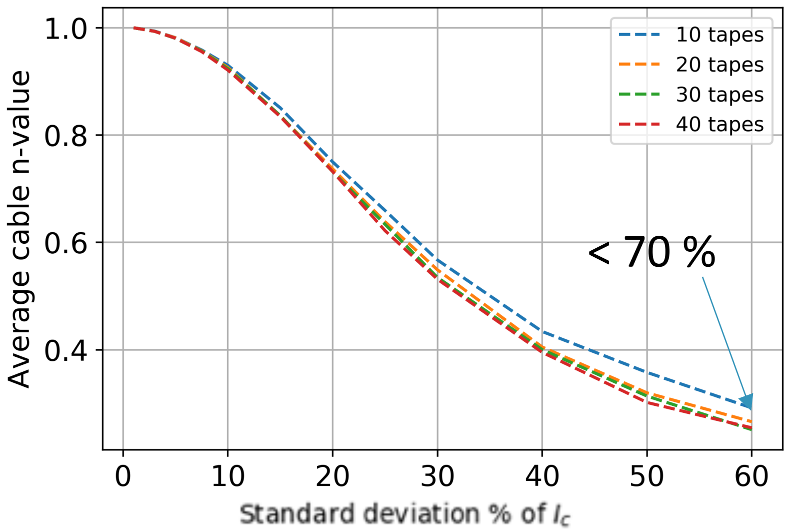
Tapes with different Ic affect the cable n value more than the cable Ic

< 1.25 %



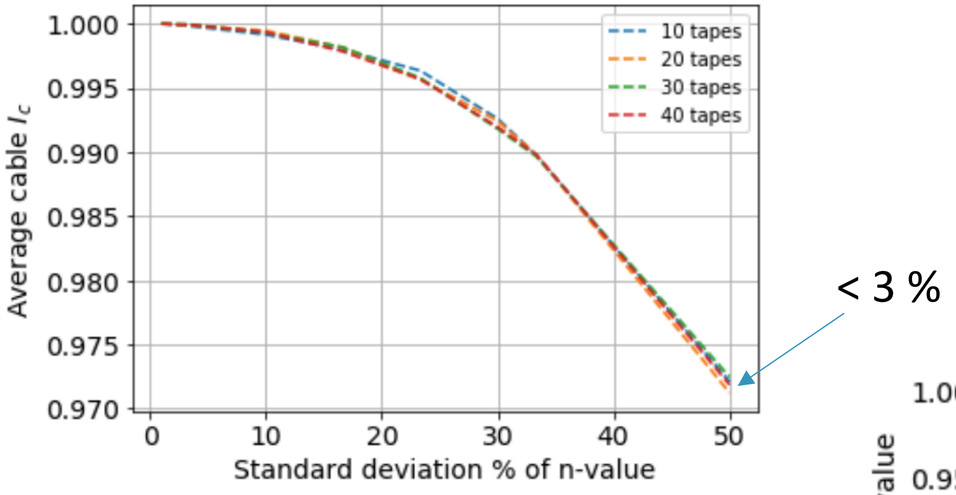
< 20 %

Cable Ic reduces by less than 5% when σ(Ic) < 30%

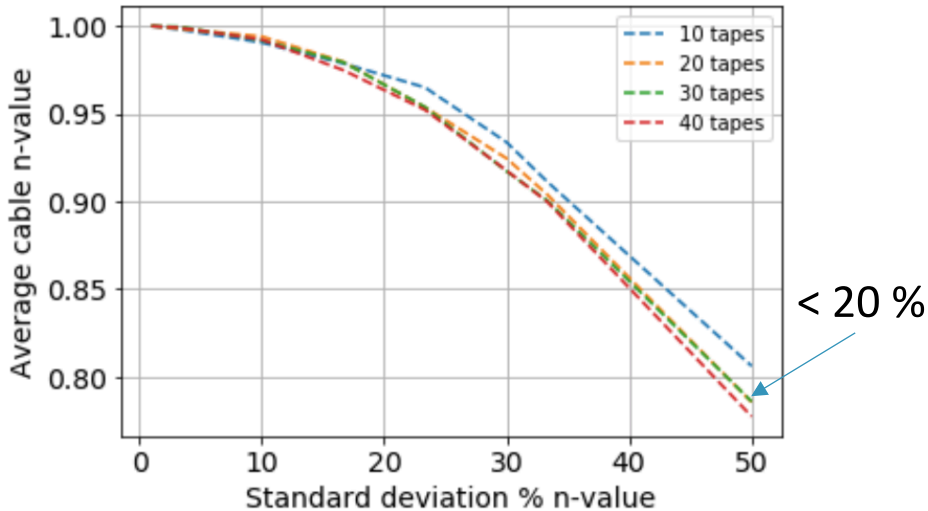


Cable n reduces by less than 50% when σ(Ic) < 30%

Tapes with different n values affect less cable Ic and n-value than tapes with different Ic values



Cable Ic reduces by less than 1% when σ(n) < 30%



Cable n reduces by less than 10% when σ(n) < 30%

Conclusions and next steps

- We developed a simple circuit model to help understand the impact of contact resistance and current sharing for REBCO cables
  - The model reproduces the published results on stacked-tape cable
  - Qualitative agreement with measurements in 2-tape stack cable soldered and with insulation

- As expected, low contact resistance allows current to bypass defects and to reduce the power generation during the transition. The value for the R_c to achieve good contact depends on the termination resistance.

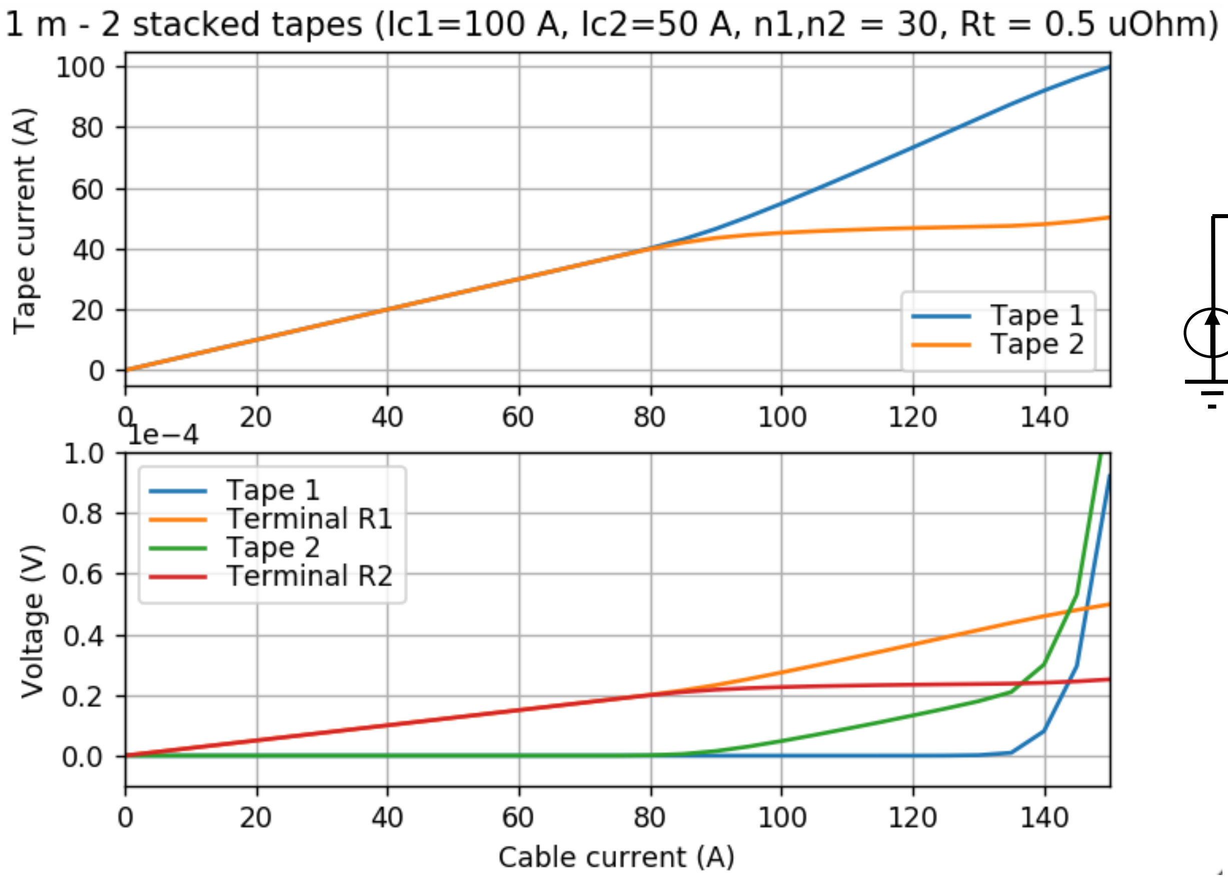
- Cable I_c and n-value are more affected by the variation of I_c in the tapes than the variation of n-value. Cable Ic reduces by less than 5% when σ(Ic) < 30%.

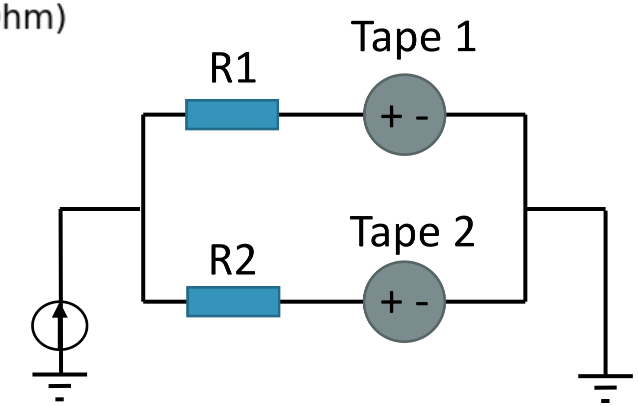
We are now working to

- Include inductances in the cable model to study the non steady-state cases
- Develop an model for CORC wire to understand the impact of contact resistance

Additional slides

We can understand the voltage and current distribution in a 2-tape cable





The current in each tape is determined by the voltage of the tape that has reach its critical current value.