Thermal analysis of quench-heater heating stations using STEAM-BBQ

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Acknowledgements
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E. Ravaioli, M. Wozniak, F. Murgia and the STEAM team

STEAM – BBQ

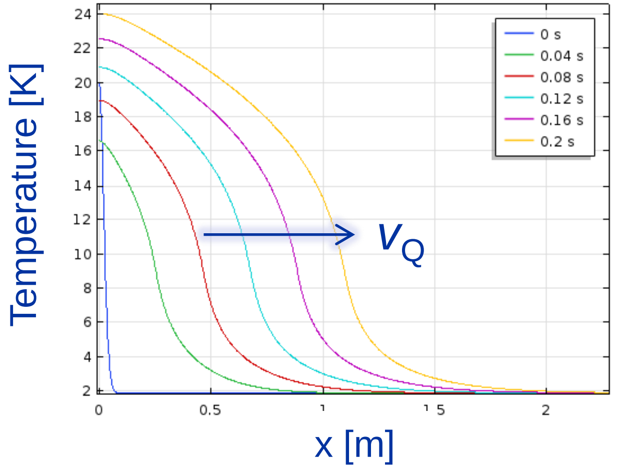
- **FEM-based COMSOL simulation model for:**

Calculation of quench-related conductor properties

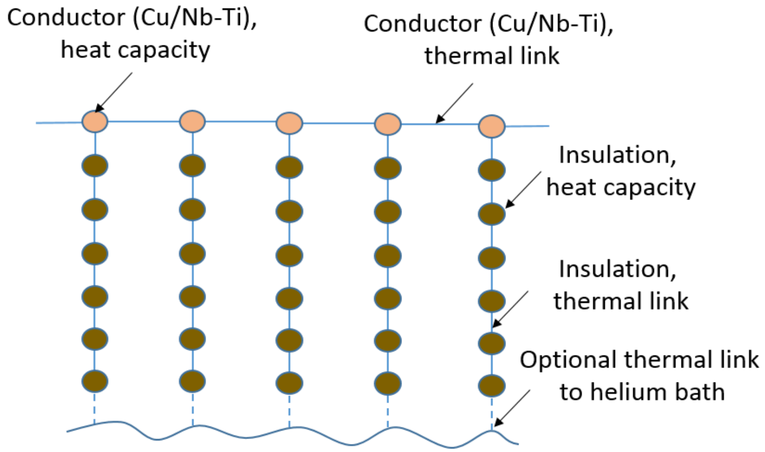
  - Quench propagation velocity
  - Development of voltage after quench origination for quench detection
  - Hotspot temperature as a function of quench integral

For circuit with known discharge quench integral:

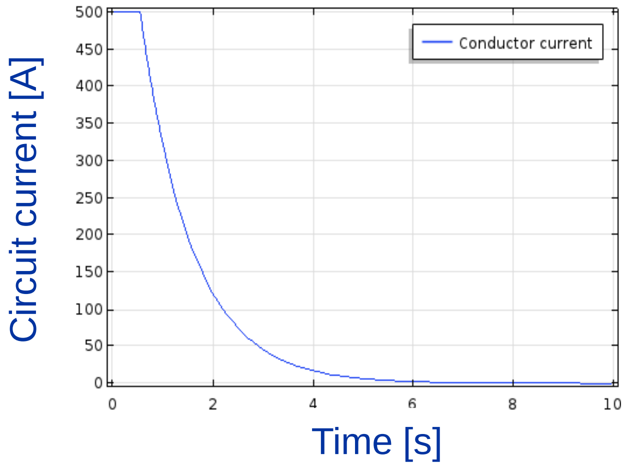
  - Time-dependent current (Exponential decay after quench detected)
  - Time-dependent hotspot temperature



Temperature-development along length of conductor



Thermal layout of BBQ: 1+1D geometry, where insulation is subdivided into six layers.

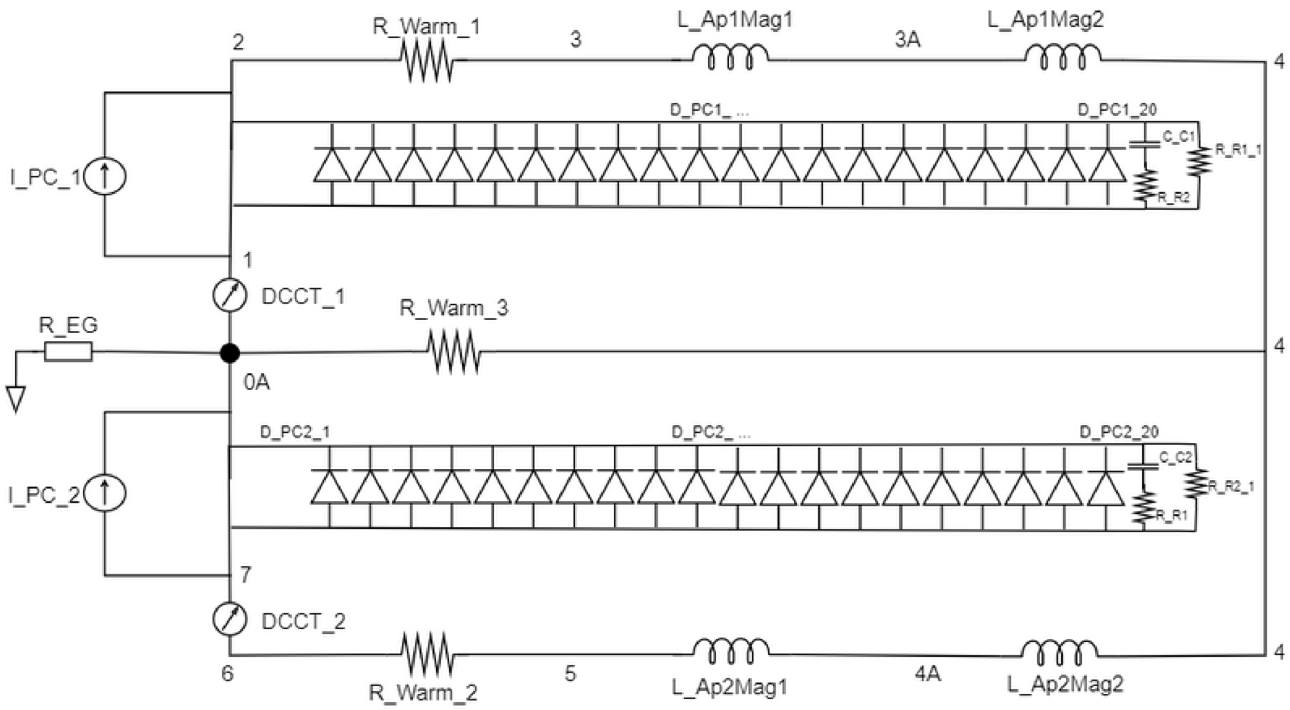


Circuit current discharge

Acknowledgement *to Matthias Mentink*
1st STEAM workshop, 13-14 June 2019
https://indico.cern.ch/event/808547/contributions/3367239/

Simulation of quench transients in nested circuits

- LHC IPQ circuits are the Individually Powered Quadrupoles in the matching sections



2x power supplies
2x different complex superconducting magnets
3x branches of which two contain each one apperture of the two powered magnets
2x complex superconducting magnets

→ Unbalanced currents in the two power supplies cause complex transients due to the strong coupling of the apertures

→ Validation was conducted
in STEAM-COSIM [PSPICE+LEDET]

F. Murgia, „Multiphysics Modelling of the LHC Individually Powered Quadrupole Superconducting Circuits"
https://cds.cern.ch/record/2729131/files/CERN-THESIS-2020-102.pdf

Quench heater on superconducting magnets

- Quench heater (QH) are stainless steel strips, attached to the outside of superconducting coils

Discharge of capacitor bank into strips

Strips can be attached to turns in zig-zag/ straight…

Quench detection → **Quench heater firing** → **Strips quickly heat up** → **Heat diffuses into attached coil turns** → **Turns transition into normal state**

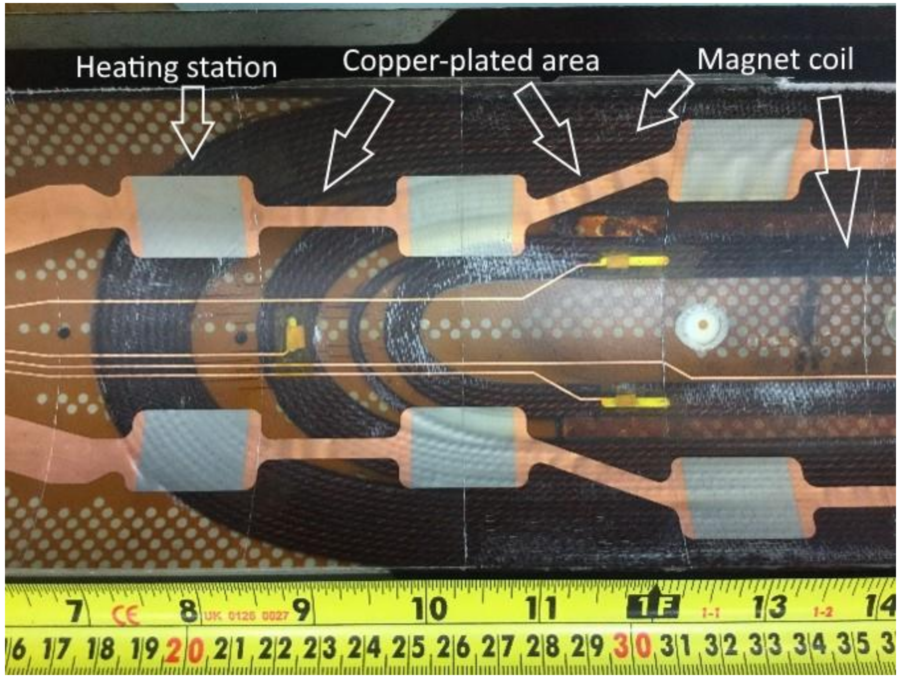
Quench Protection

Voltage taps etc.

High voltage across strips

- In order to limit the voltage, that needs to be applied, some parts of the strips are plated with copper
  → Stainless steel areas remain as heating stations

- From the parts attached to the heating stations, the normal zone is propagating along the turn between heating stations and to other turns



Quench propagation velocity

- Usually: Magnets protected with QH are quenched so fast, that a 2D model is sufficient
  for example for most magnets at nominal current

- But: For lower current level, the effect of the quench propagation velocity can impact the discharge

Quench propagation velocity v_Q in STEAM-LEDET

- Calculated using an analytic equation
- Scales the electrical resistance of each turn, based on the quenched fraction
- Assumes adiabatic conditions (cooling is neglected)

$$v_q = \frac{J}{\bar{c}} \left(\frac{pk}{T_{cs}/2 + T_c/2 - T} \right)^{1/2}$$

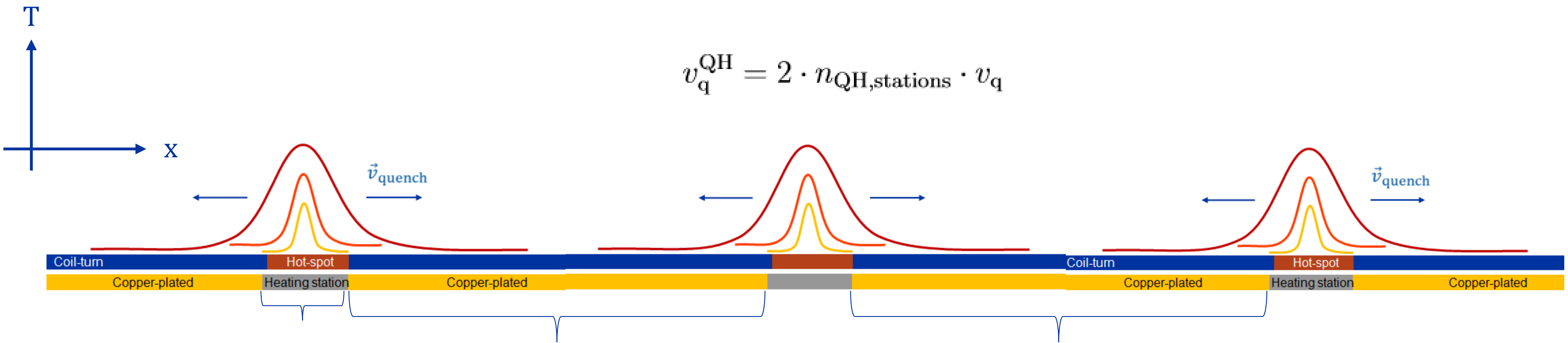
[*]

[*] H. ten Kate, H. Boschman and L. Van de Klundert, "Longitudinal propagation velocity of the normal zone in superconducting wires", *IEEE Trans. Magn.*, vol. 23, no. 2, pp. 1557-1560, Mar. 1987

Effect of heating station on the quench propagation velocity

- After the QH firing, the normal zone is propagating from each heating station into both, longitudinal directions

$$v_q^{QH} = 2 \cdot n_{QH,stations} \cdot v_q$$



Example MQM magnet: 120mm 170mm 170mm

vQ @ nominal current: ~20m/s 8,5 ms 8,5 ms

All turns, attached to QH would quench in ~8.5ms at nominal current

vQ @ 3 kA: ~7m/s 25 ms 25 ms

All turns, attached to QH would quench in ~25ms at 3 kA

Infiltrated helium in superconducting cables

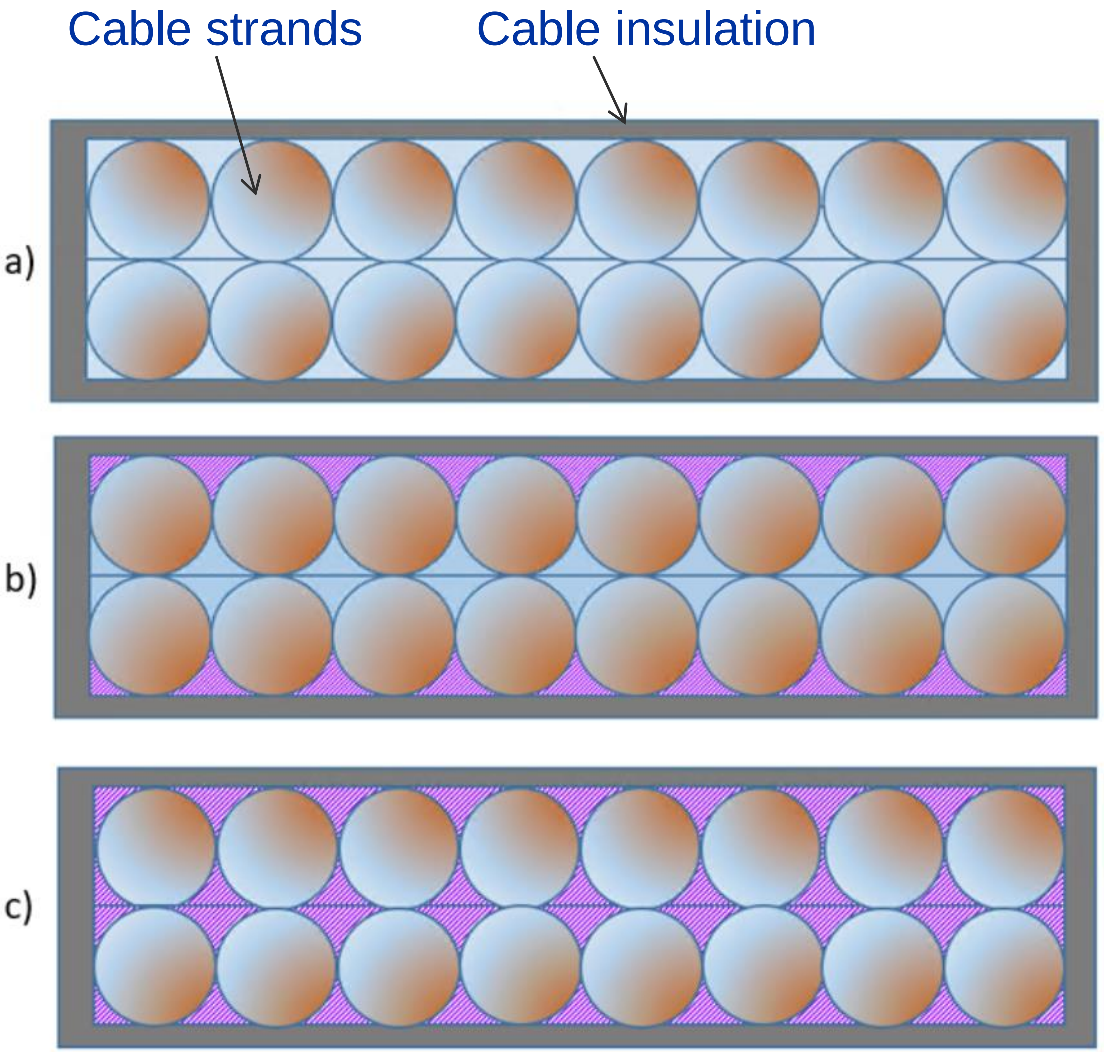
- Superliquid helium can infiltrate into the cable voids, because of its special properties

→The cooling significantly changes vQ for lower current level

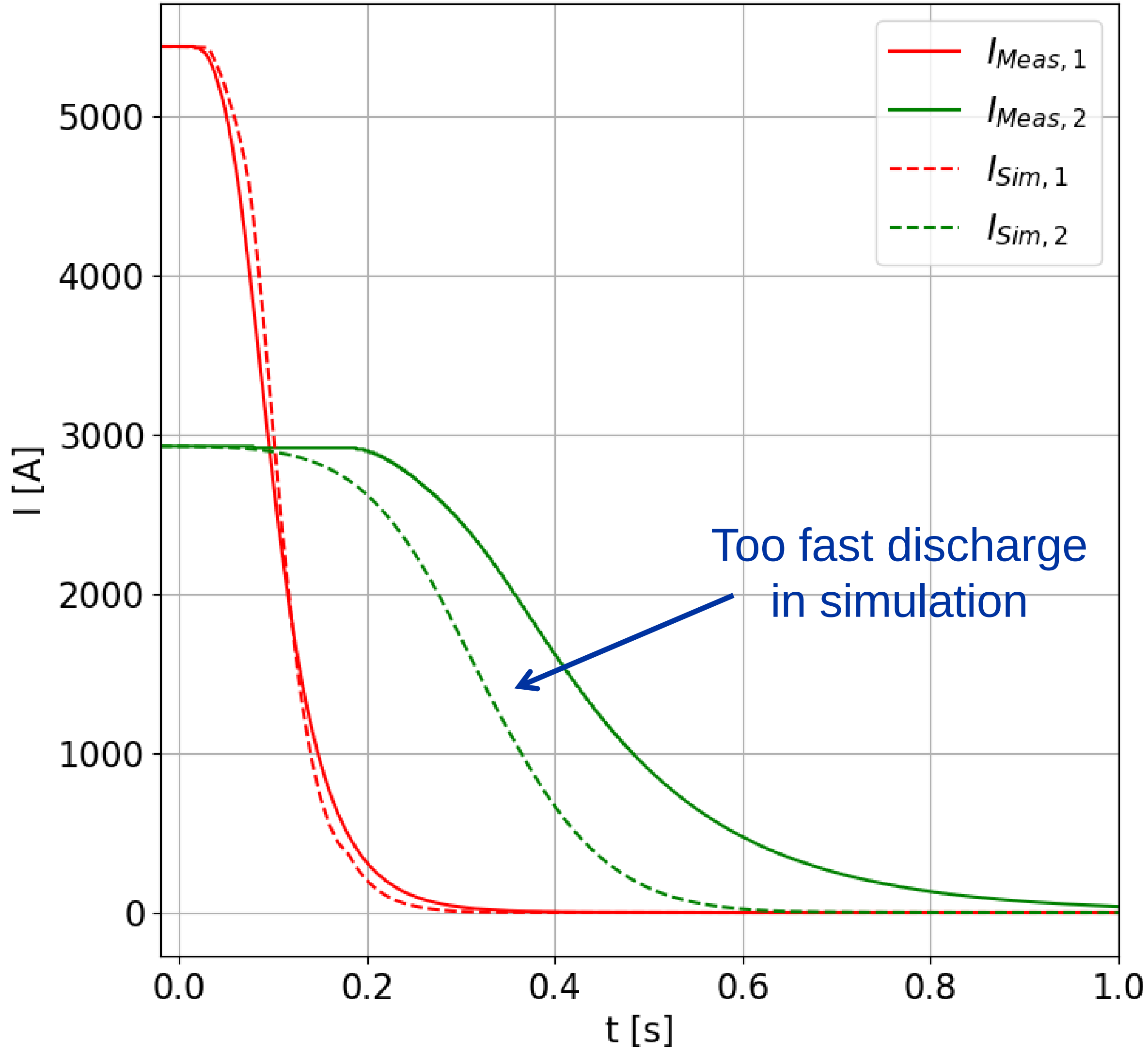
a) All voids are filled with helium

b) Half of the voids are filled with helium, remaining parts filled with insulation

c) All voids are filled with insulation and no helium creeped into the cables voids



Problem: Unbalanced currents



Too fast discharge in simulation

Typical transient in the IPQ branches (Measurements vs. Simulation)

-Parameter sets of these magnets, were validated in STEAM-LEDET and STEAM-COSIM

- Very good agreement for the higher current case, poor agreement for lower current level

→ Effect has to be current dependent

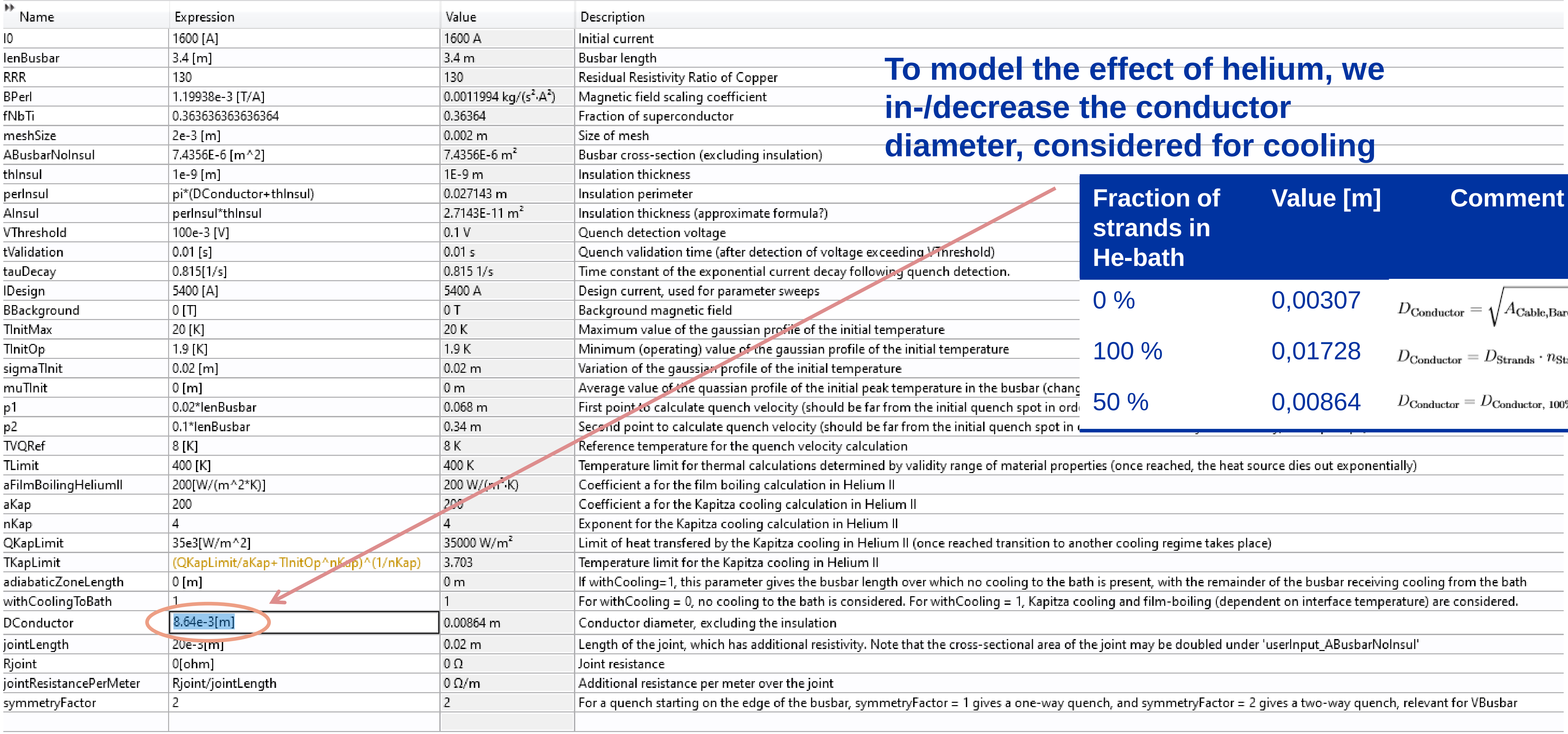
- Using the quench velocity in STEAM-LEDET, we assume **adiabatic conditions**

  → *Acceptable for fast transients at high current*

  → *Cooling and its effect on the quench propagation might play a significant role on lower current level*

→ Thermal analysis in STEAM-BBQ

BBQ: User-interface – Modelling infiltrated He

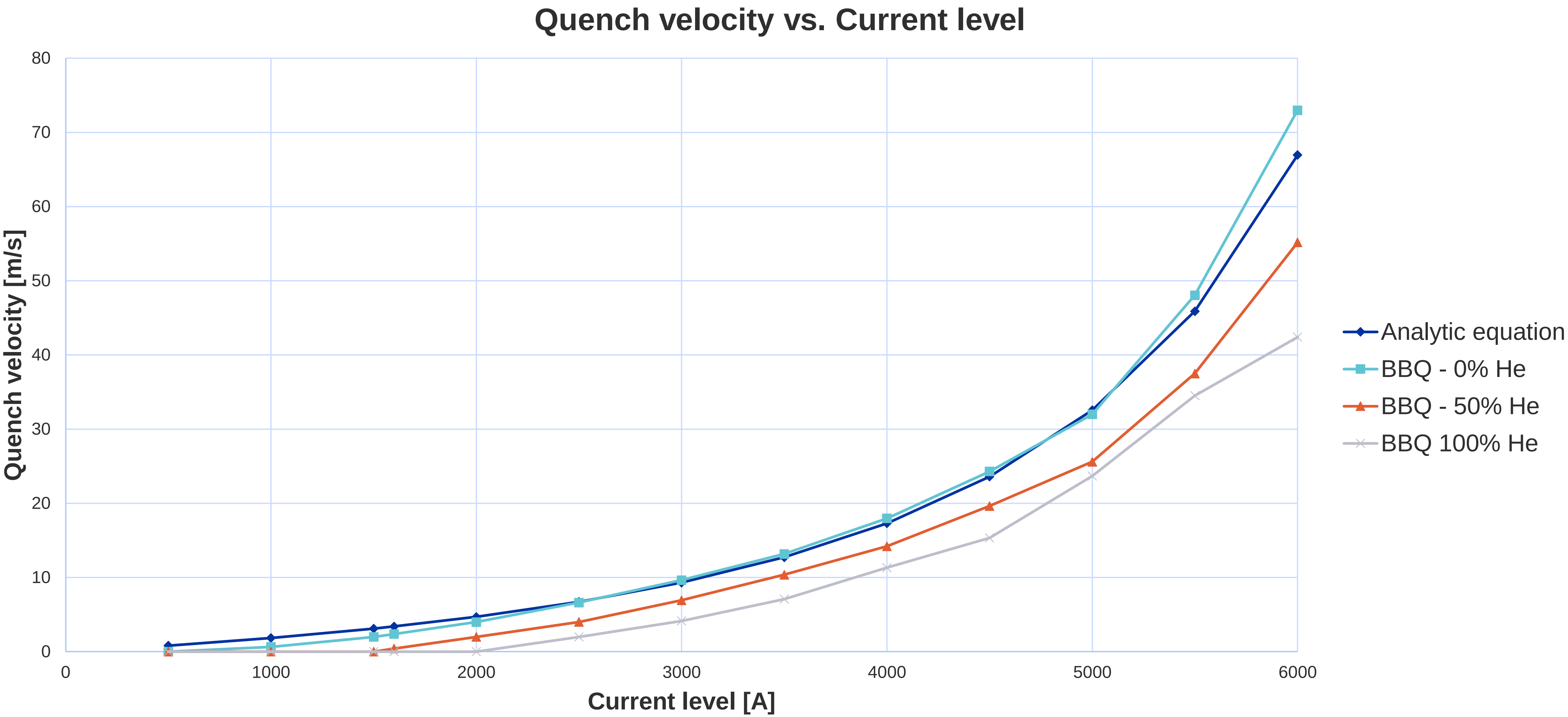


Name	Expression	Value	Description
I0	1600 [A]	1600 A	Initial current
lenBusbar	3.4 [m]	3.4 m	Busbar length
RRR	130	130	Residual Resistivity Ratio of Copper
BPerI	1.19938e-3 [T/A]	0.0011994 kg/(s²·A²)	Magnetic field scaling coefficient
fNbTi	0.363636363636364	0.36364	Fraction of superconductor
meshSize	2e-3 [m]	0.002 m	Size of mesh
ABusbarNoInsul	7.4356E-6 [m^2]	7.4356E-6 m²	Busbar cross-section (excluding insulation)
thInsul	1e-9 [m]	1E-9 m	Insulation thickness
perInsul	pi*(DConductor+thInsul)	0.027143 m	Insulation perimeter
AInsul	perInsul*thInsul	2.7143E-11 m²	Insulation thickness (approximate formula?)
VThreshold	100e-3 [V]	0.1 V	Quench detection voltage
tValidation	0.01 [s]	0.01 s	Quench validation time (after detection of voltage exceeding VThreshold)
tauDecay	0.815[1/s]	0.815 1/s	Time constant of the exponential current decay following quench detection.
IDesign	5400 [A]	5400 A	Design current, used for parameter sweeps
BBackground	0 [T]	0 T	Background magnetic field
TInitMax	20 [K]	20 K	Maximum value of the gaussian profile of the initial temperature
TInitOp	1.9 [K]	1.9 K	Minimum (operating) value of the gaussian profile of the initial temperature
sigmaTInit	0.02 [m]	0.02 m	Variation of the gaussian profile of the initial temperature
muTInit	0 [m]	0 m	Average value of the quassian profile of the initial peak temperature in the busbar (chang
p1	0.02*lenBusbar	0.068 m	First point to calculate quench velocity (should be far from the initial quench spot in ord
p2	0.1*lenBusbar	0.34 m	Second point to calculate quench velocity (should be far from the initial quench spot in
TVQRef	8 [K]	8 K	Reference temperature for the quench velocity calculation
TLimit	400 [K]	400 K	Temperature limit for thermal calculations determined by validity range of material properties (once reached, the heat source dies out exponentially)
aFilmBoilingHeliumII	200[W/(m^2*K)]	200 W/(m²·K)	Coefficient a for the film boiling calculation in Helium II
aKap	200	200	Coefficient a for the Kapitza cooling calculation in Helium II
nKap	4	4	Exponent for the Kapitza cooling calculation in Helium II
QKapLimit	35e3[W/m^2]	35000 W/m²	Limit of heat transfered by the Kapitza cooling in Helium II (once reached transition to another cooling regime takes place)
TKapLimit	(QKapLimit/aKap+TInitOp^nKap)^(1/nKap)	3.703	Temperature limit for the Kapitza cooling in Helium II
adiabaticZoneLength	0 [m]	0 m	If withCooling=1, this parameter gives the busbar length over which no cooling to the bath is present, with the remainder of the busbar receiving cooling from the bath
withCoolingToBath	1	1	For withCooling = 0, no cooling to the bath is considered. For withCooling = 1, Kapitza cooling and film-boiling (dependent on interface temperature) are considered.
DConductor	8.64e-3[m]	0.00864 m	Conductor diameter, excluding the insulation
jointLength	20e-3[m]	0.02 m	Length of the joint, which has additional resistivity. Note that the cross-sectional area of the joint may be doubled under 'userInput_ABusbarNoInsul'
Rjoint	0[ohm]	0 Ω	Joint resistance
jointResistancePerMeter	Rjoint/jointLength	0 Ω/m	Additional resistance per meter over the joint
symmetryFactor	2	2	For a quench starting on the edge of the busbar, symmetryFactor = 1 gives a one-way quench, and symmetryFactor = 2 gives a two-way quench, relevant for VBusbar

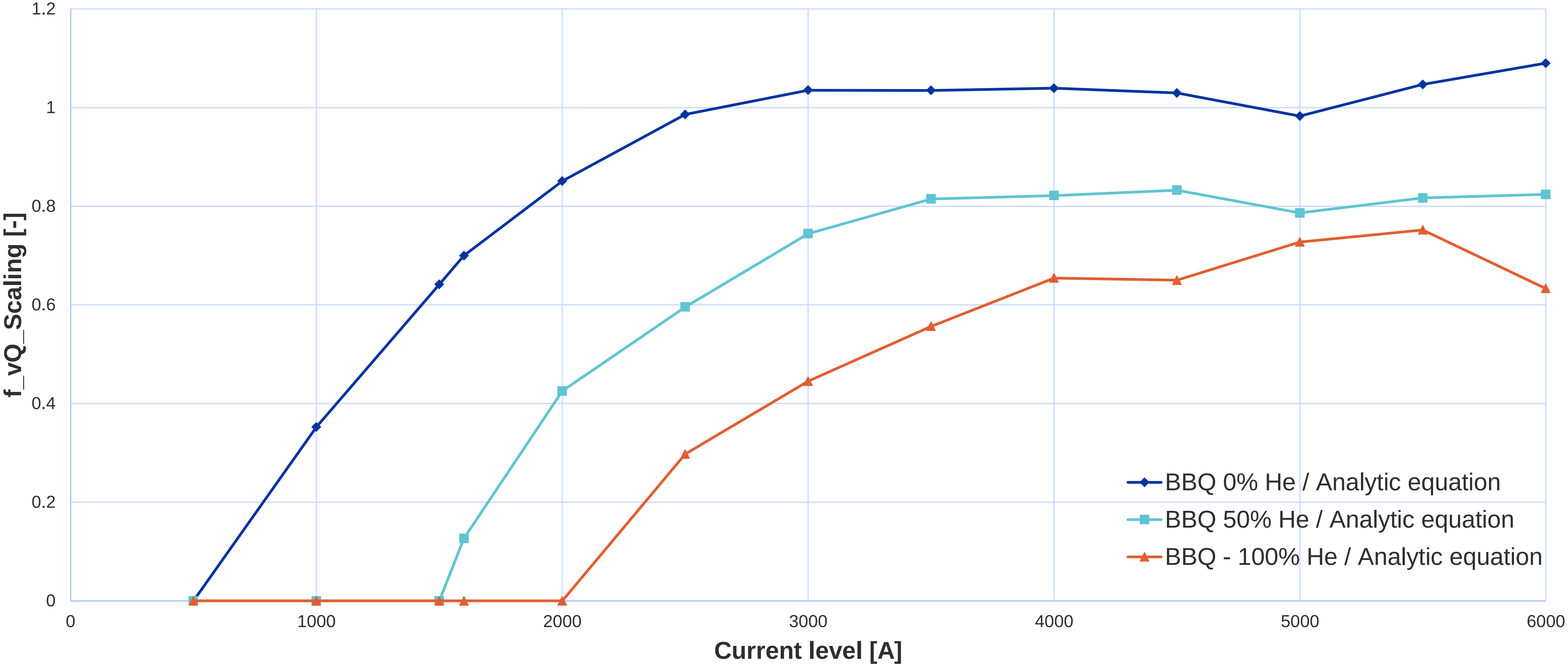
To model the effect of helium, we in-/decrease the conductor diameter, considered for cooling

Fraction of strands in He-bath	Value [m]	Comment
0 %	0,00307	$D_{\text{Conductor}} = \sqrt{A_{\text{Cable,Bare}} \cdot \frac{4}{\pi}}$
100 %	0,01728	$D_{\text{Conductor}} = D_{\text{Strands}} \cdot n_{\text{Strands}}$
50 %	0,00864	$D_{\text{Conductor}} = D_{\text{Conductor, 100\%}}/2$

Calculated quench propagation velocities

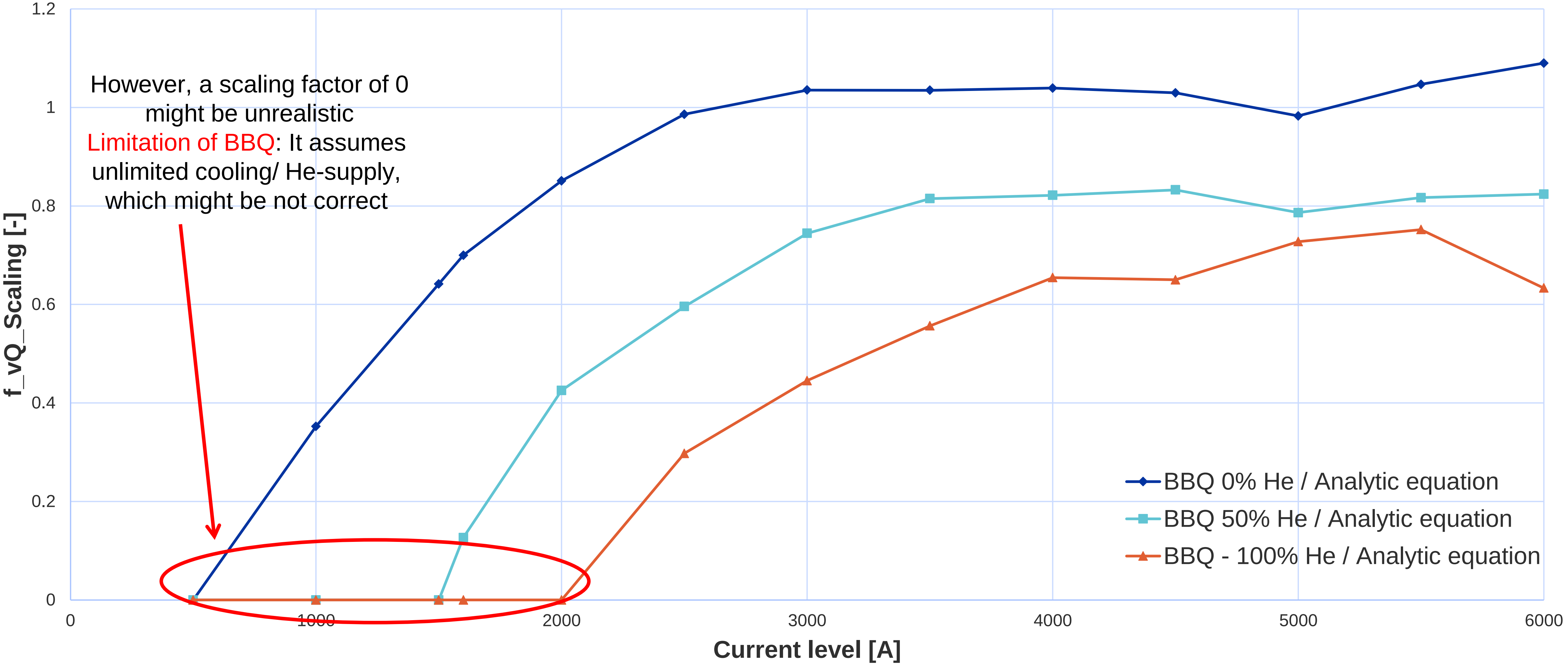


Scaling factor for the quench velocity



→ Cooling in the cable voids can significantly decrease the quench velocities, especially on lower current level

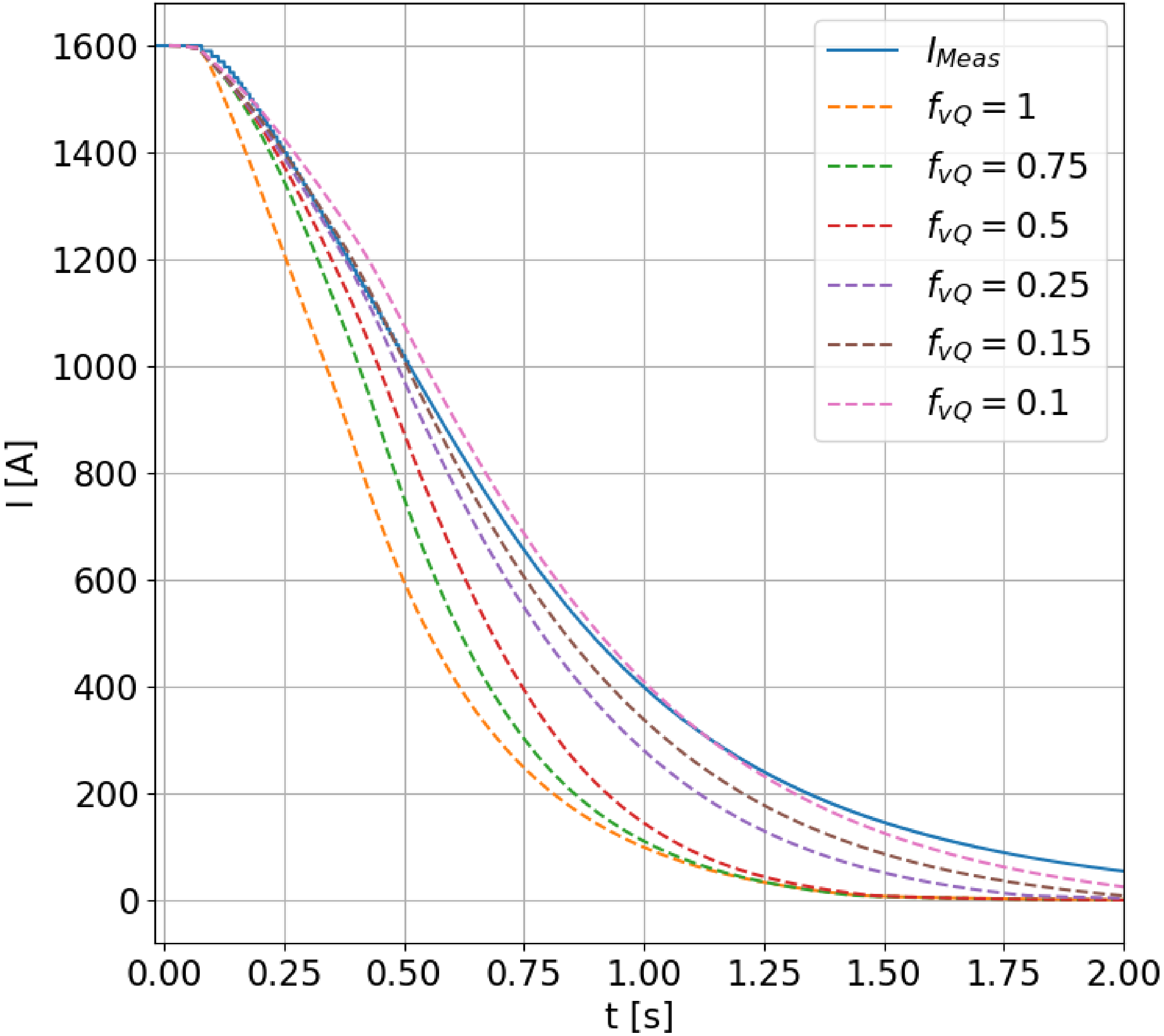
Scaling factor for the quench velocity



However, a scaling factor of 0 might be unrealistic
Limitation of BBQ: It assumes unlimited cooling/ He-supply, which might be not correct

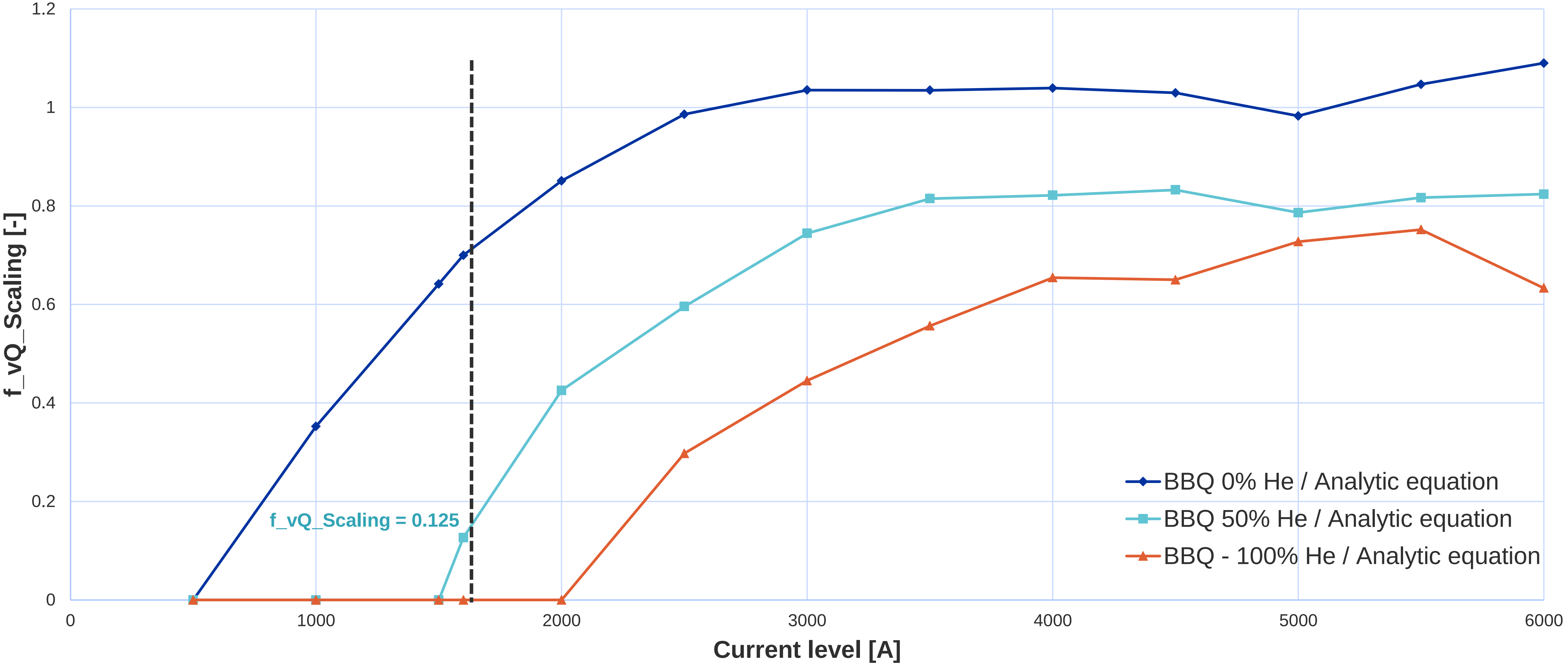
→ Cooling in the cable voids can significantly decrease the quench velocities, especially on lower current level

Comparison of simulations including scaling factor



→ Quench propagation velocity needs to be decreased by a factor ~1/8

Scaling factor for the quench velocity



→ Applying the BBQ scaling factor at low current level, leads to the best fit in STEAM-LEDET

Conclusion

- During the validation of IPQ circuits, an „unknown“ current level dependent effect was noticed

- At lower current level, the calculation of quench velocity, assuming adiabatic condition, does not lead to a good agreement with measurements

- STEAM-BBQ was used to better estimate the quench velocity on lower current level

→Different scaling factors for 0, 50 and 100% infiltrated helium in the cable voids were deduced

- Applying these scaling factors to the STEAM-LEDET and STEAM-COSIM simulation lead to a better fit at lower current level