Stability Analysis of the Interconnection of the LHC Main Superconducting Bus Bars

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Acknowledgments

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Outline

- Stability analysis of the LHC Main SC Bus Bar Interconnections
  - Model description
  - Effect of parameters in adiabatic conditions
  - Effect of parameters with heat transfer to helium

- Heat Transfer (HT) Mechanisms
  - in the Bus Bar region: analysis of dedicated test, impact on stability
  - in the Interconnection region: analysis of the FRESCA test, impact on stability

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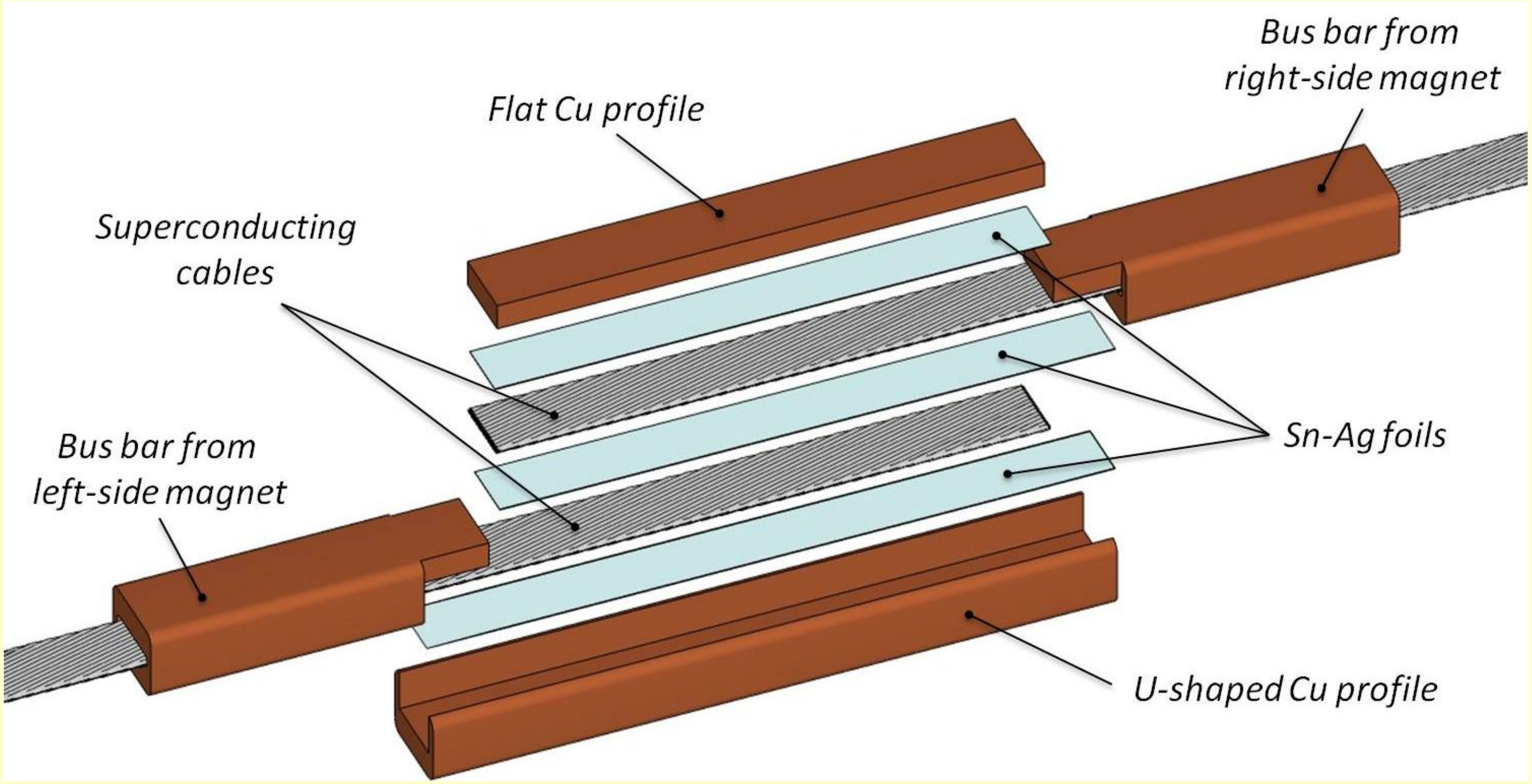
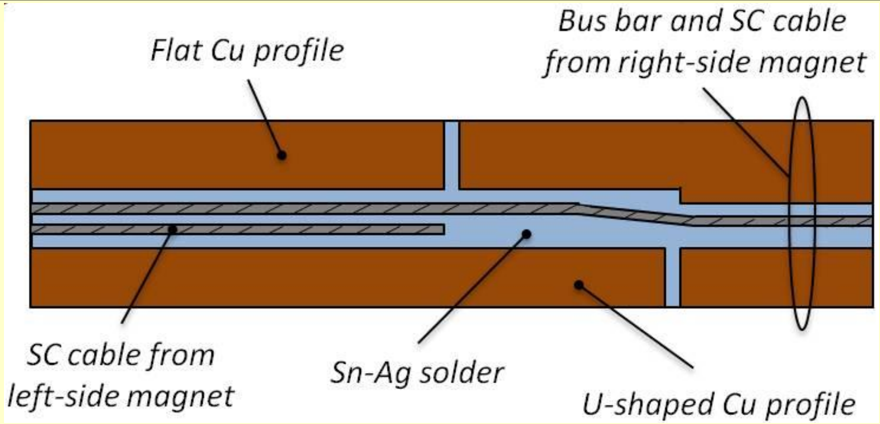
Main Bus Bar Interconnections (1/2)

- The analysis is based on this design of the Main Bus Bar Interconnections (without Shunt)



Main Bus Bar Interconnections (2/2)

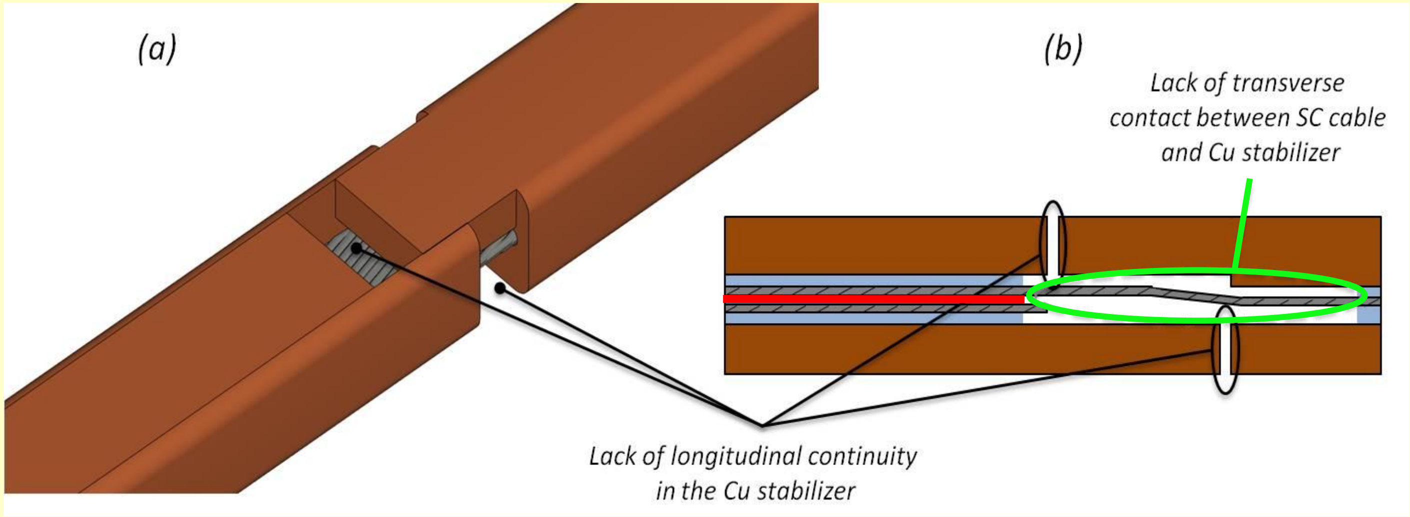


Good joints:

R_{el} (RT) ~ 12 μΩ

Incident

1) bad contact between SC cables;
2) transverse lack of solder;
3) interruption between joint and bus stabilizer.



The additional resistance

- The R_{16} electrical resistance measurements is measured over a 16 cm length across the splice to detect splices with a high excess resistance in the NC state [1]

$$R_{add} = R_{16} - R_{16,good}$$

$$R_{16,good} \begin{cases} \sim 12\ \mu\Omega \text{ for MB} \\ \sim 19\ \mu\Omega \text{ for MQ} \end{cases}$$

- Measured R_{add} up **to ~ 60 μΩ**

- The additional resistance can be correlated to the length of the defect by the following equation evaluated at room temperature:

$$\frac{\rho_{el}}{n_{st} \cdot A_{st} \cdot {A_{Cu}}/{(A_{Cu}+A_{SC})}} \, [\Omega / m]$$

[1] F. Bertinelli et al., "*Towards a consolidation of LHC Superconducting Splices for 7 TeV Operation*", 1st International Particle Accelerator Conference, Kyoto, Japan, 23-28 May 2010

THEA model (1/2)

THEA is a multi-physics model:

- Heat conduction in solid components
- Compressible flow in cooling channels
- Current distribution in electrical components

Bus Bar and Interconnection model

- single homogeneous thermal element
- two components, Nb-Ti and Cu
- initial T = 10 K → **Quench already developed**
- adiabatic boundaries

$$A\rho\, C\frac{\partial T}{\partial t}-\frac{\partial}{\partial x}\left(A\,k\,\frac{\partial T}{\partial x}\right)+p_{He}h(T-T_{He})=\dot{q}^{'}_{Joule}$$

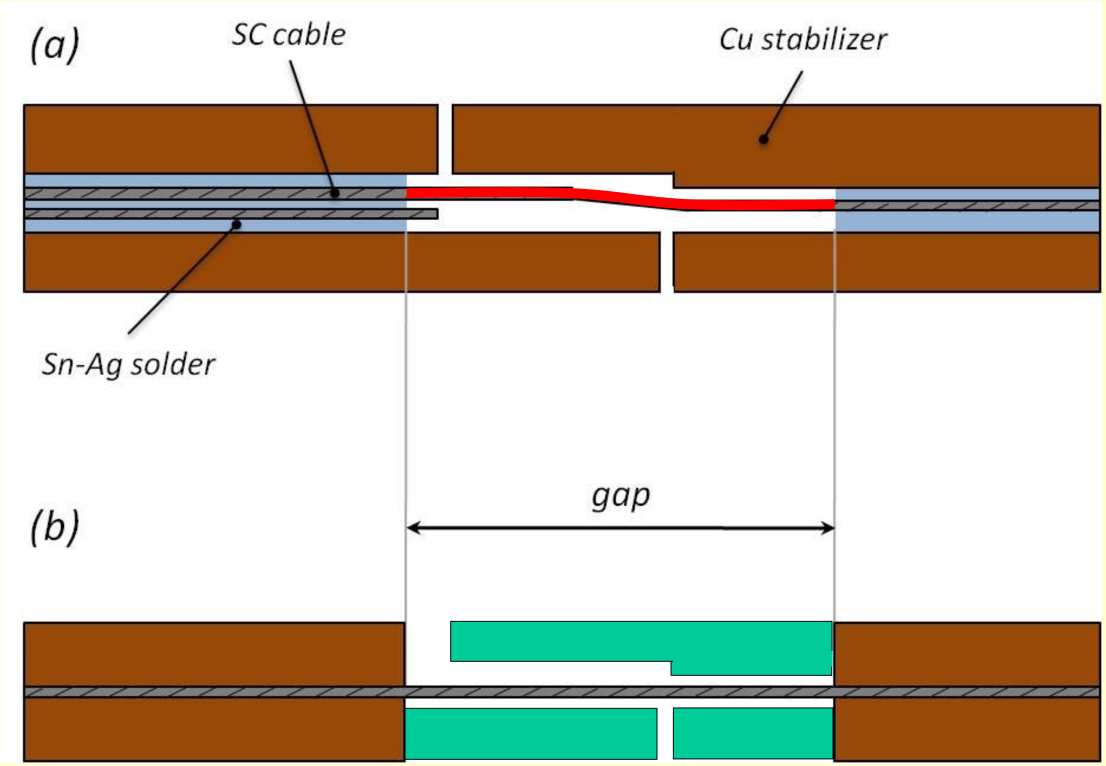
Longitudinal conduction **Q to helium.**

- The current distribution is neglected

THEA model (2/2)

Defect Model: the contemporary presence of transverse and longitudinal lack of solder is considered in calculations

Worst case for stability: the whole current is forced to flow in the SC cable copper matrix



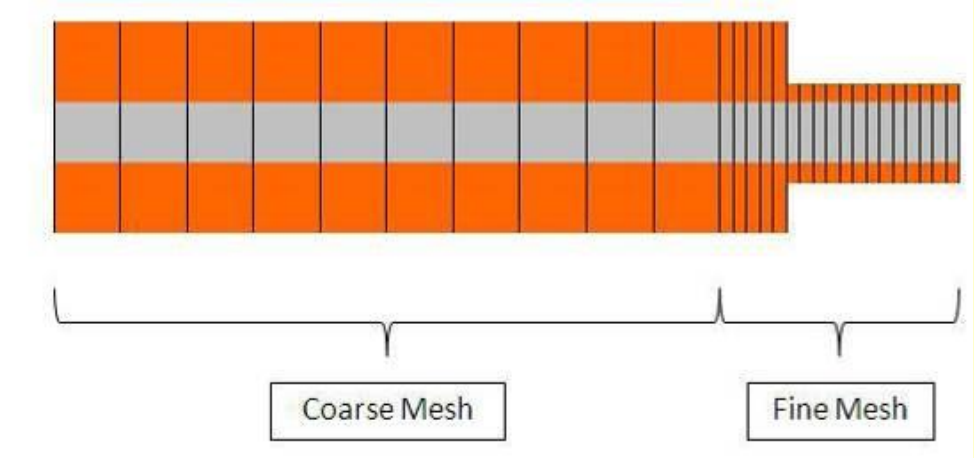
- Defect modeled as a reduction in the Cu cross section
- Neglecting the Cu not in contact with the SC cable makes the domain symmetric
- Thermal approximation: loss of heat capacity

THEA parametric analysis

Results of convergence study

- Mesh with $\Delta x < 0.5$ mm for the fine mesh region and $\Delta x < 5$ mm for the coarse mesh region

- Time steps $\Delta t < 10$ ms are necessary to catch the solution features



Stability analysis as a function of manufacturing quality, operating conditions and protection system parameters:

- Current dump time τ_{Dump}
- Copper *R*esidual *R*esistivity *R*atio *RRR*
- Spatial distribution of the lack of SnAg
- Helium cooling capability

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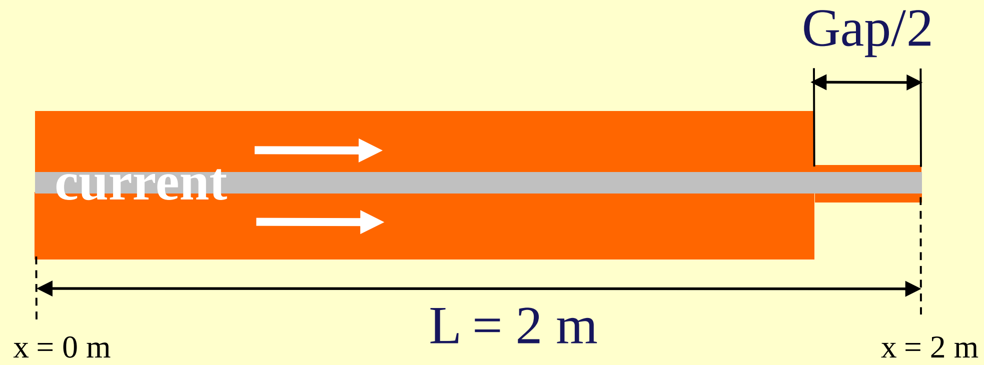
Adiabatic Model Results (1/5)

Main Bending

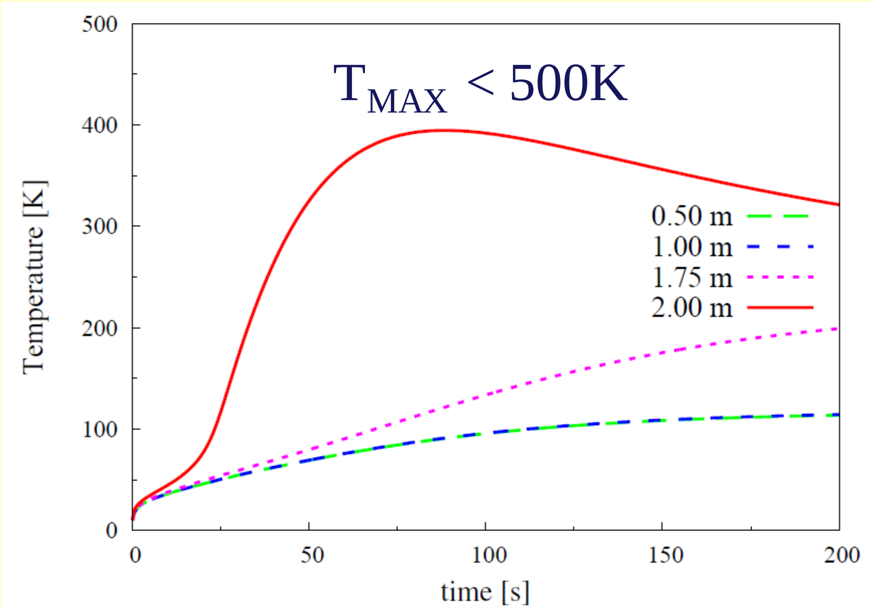
$I = 11850$ A $\tau_{det} = 0.2$ s

$B = 0.474$ T $\tau_{Dump} = 100$ s

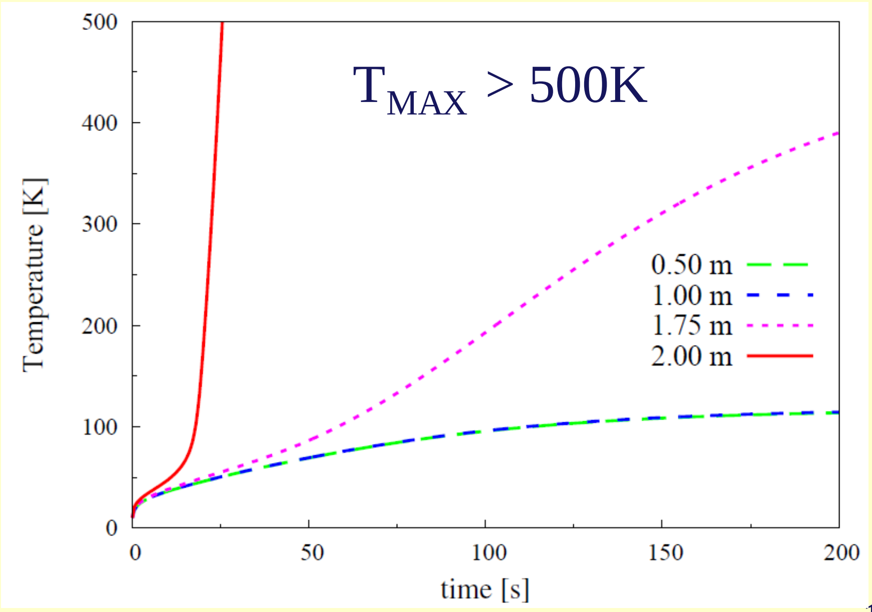
RRR (cable/bus) = 80 - 100



Gap = 7 mm



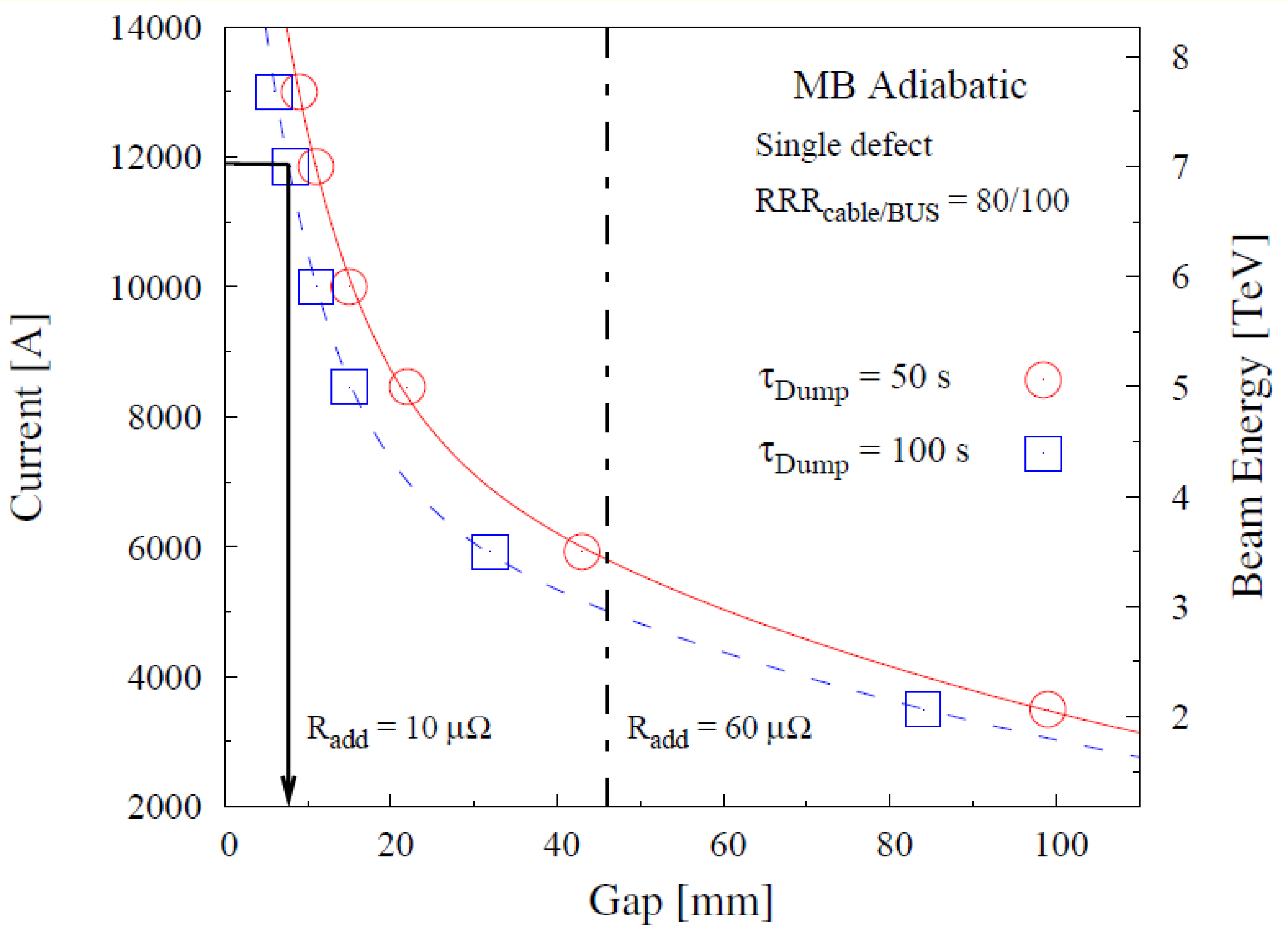
Gap = 8 mm



Adiabatic Model Results (2/5)

Aim: finding the **critical defect length** → Minimum gap length leading to $T_{MAX} > 500$ K

Stability as a function of the τ_{Dump}



Stability Improvement

3.5 TeV

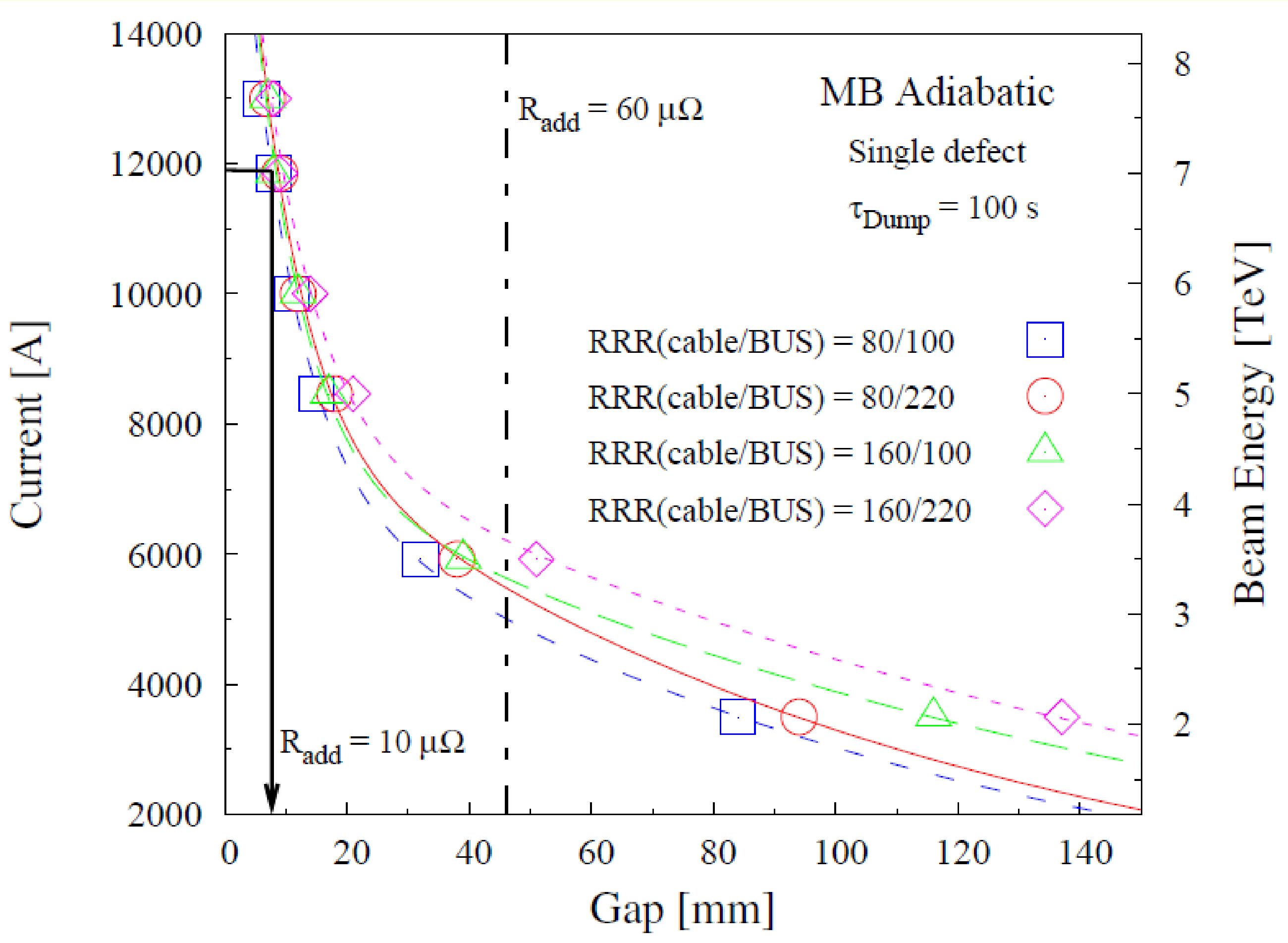
ΔR_{add} = 14.3 μΩ

4.0 TeV

ΔR_{add} = 11.7 μΩ

Adiabatic Model Results (3/5)

Stability as a function of the *RRR*



Stability Improvement

3.5 TeV

ΔR_{add} = 24.7 μΩ

4.0 TeV

ΔR_{add} = 15.6 μΩ

Adiabatic Model Results (4/5)

Spatial distribution of the lack of solder

Main Bending

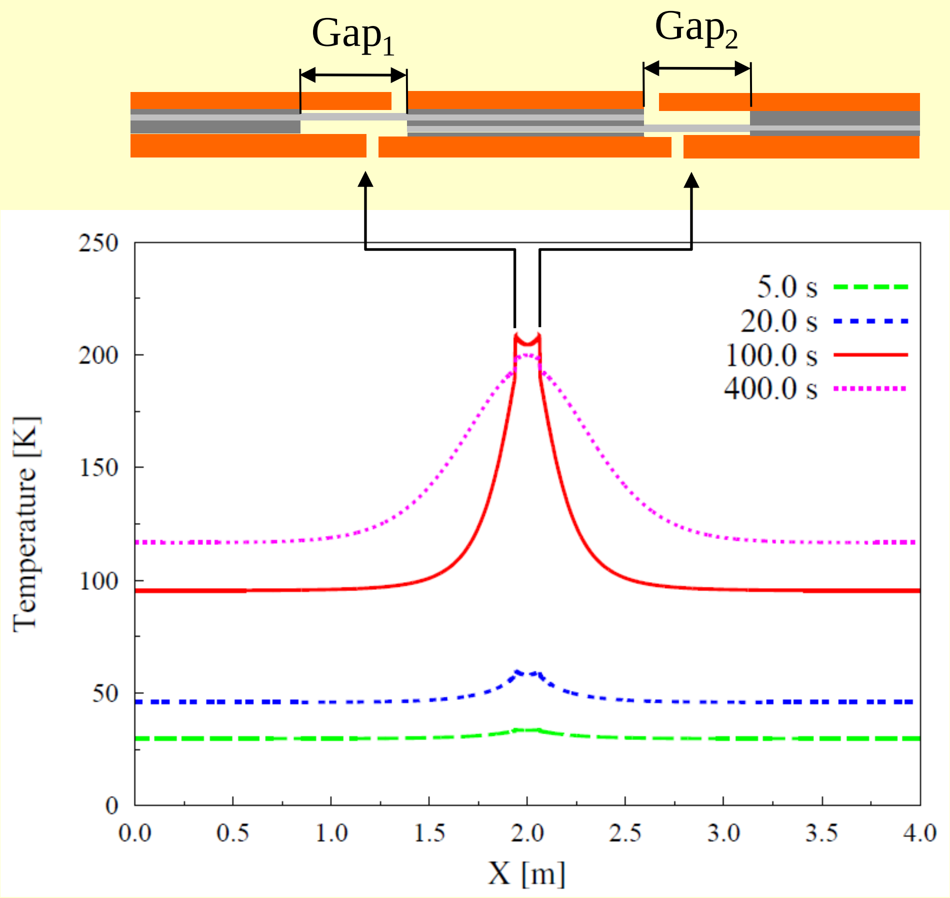
I = 11850 A τ_{det} = 0.2 s

B = 0.474 T τ_{Dump} = 100 s

RRR (cable/bus) = 80 - 100

melting **Gap = 8 mm**

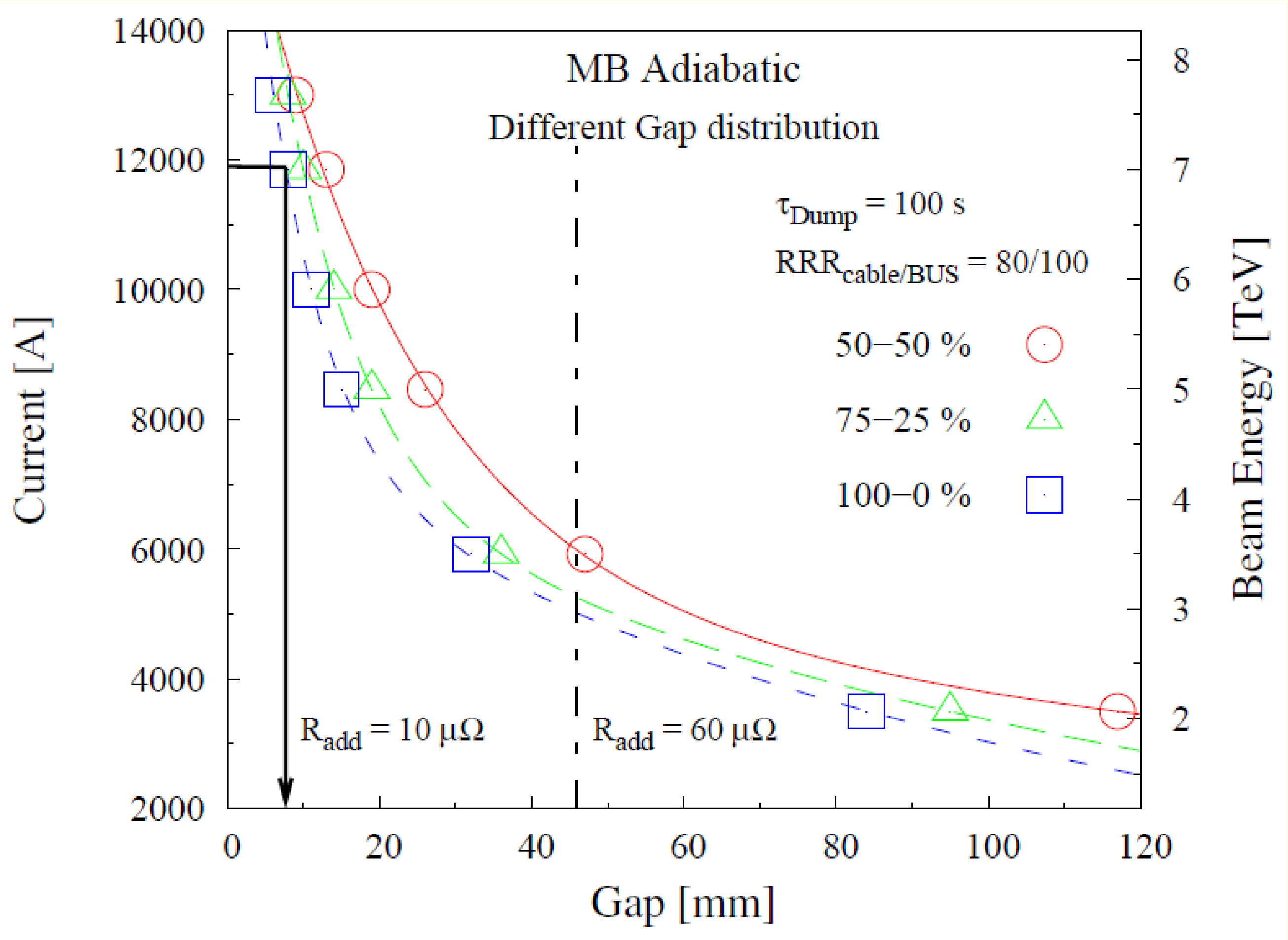
stable **Gap$_1$ = Gap$_2$ = 4 mm**



The split defect *exhibits better stability* with the same total length

Adiabatic Model Results (5/5)

Stability as a function of the *spatial distribution of the defect*



Stability Improvement

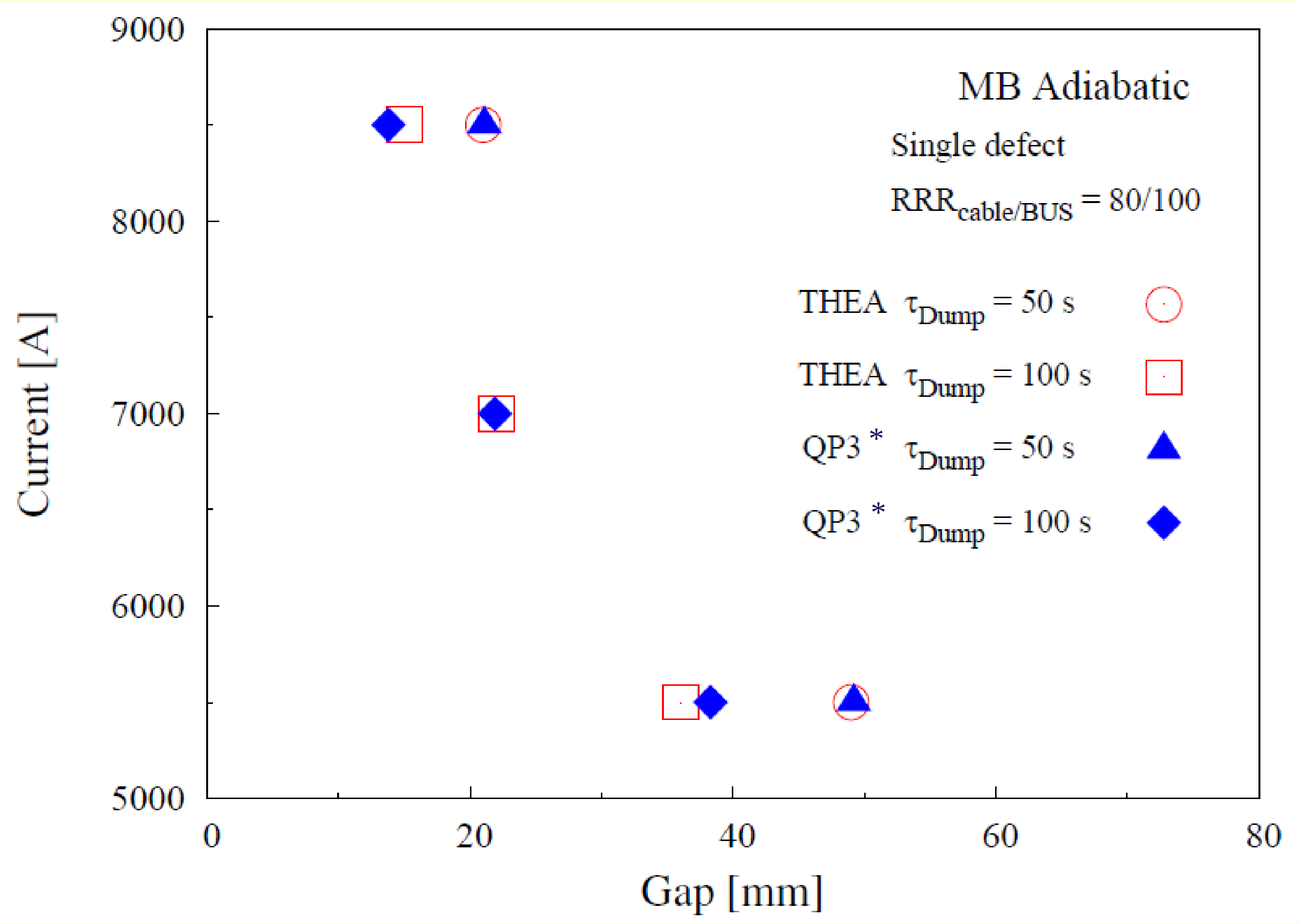
3.5 TeV

ΔR_{add} = 19.5 μΩ

4.0 TeV

ΔR_{add} = 18.5 μΩ

Comparison with model QP3 in adiabatic conditions



Differences in R_{add} between the two models are of about $0 \div 3\ \mu\Omega$

* Data courtesy of A. Verweij, TE-MPE (*Chamonix 2010 LHC Performance Workshop)*

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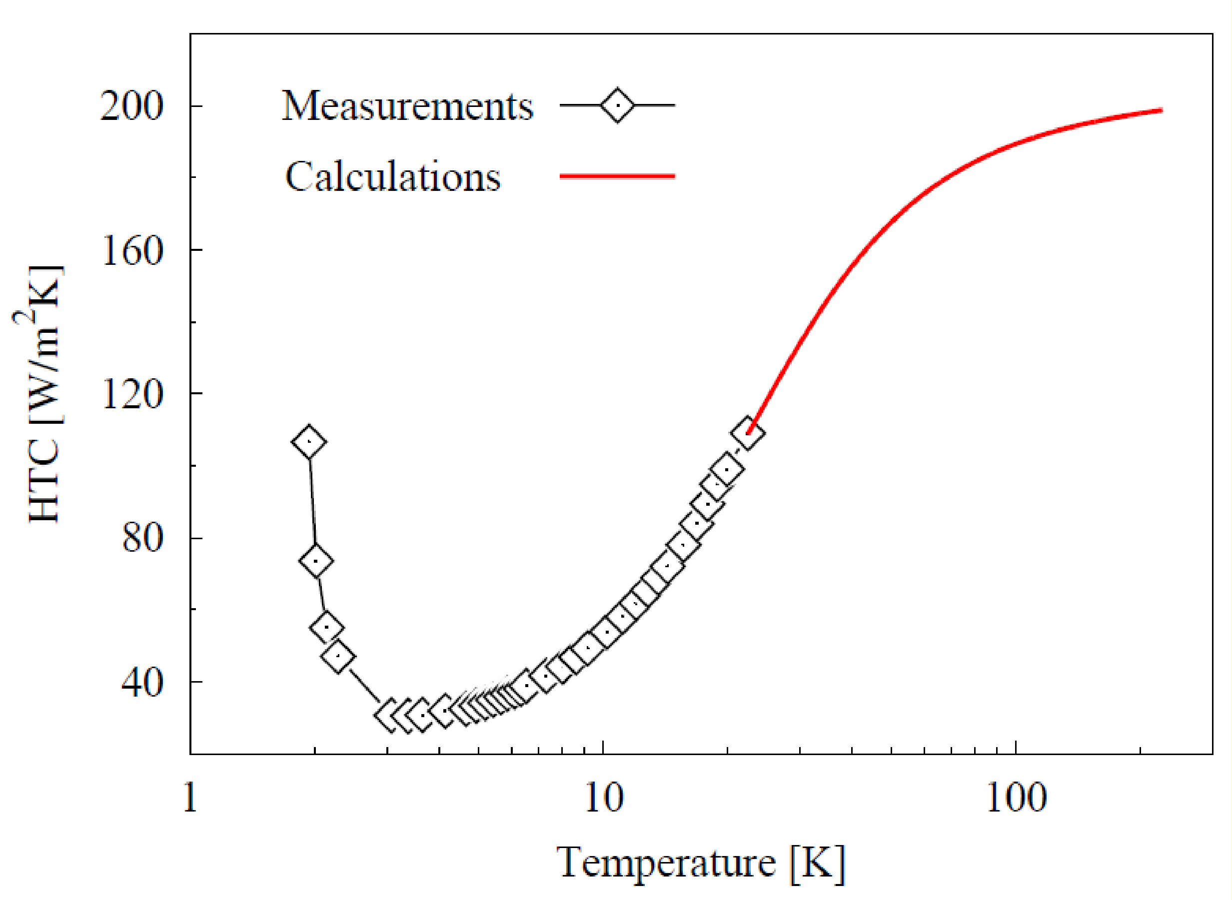
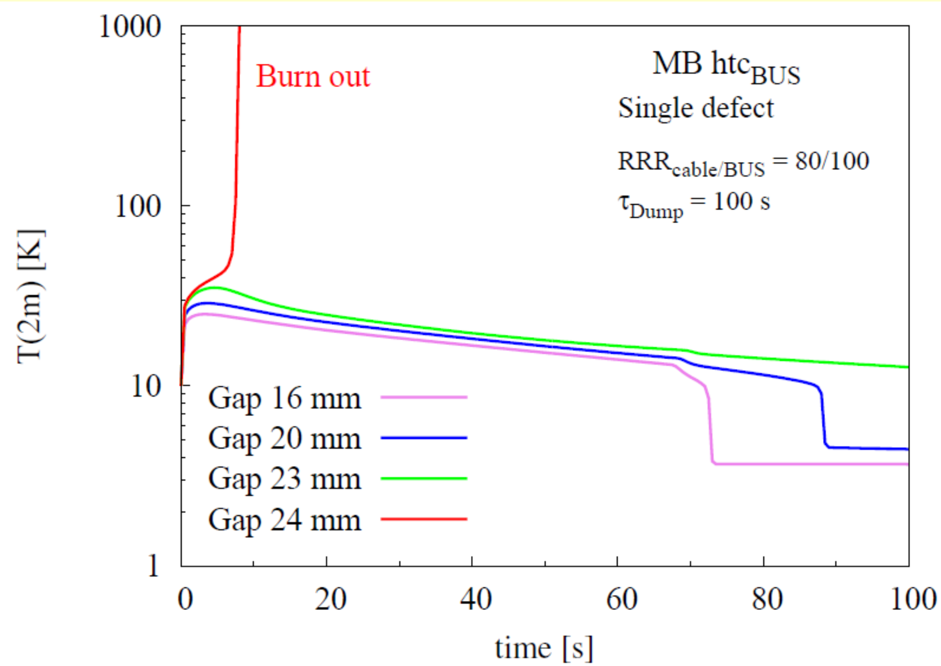
Heat Transfer to Helium Model Results (1/5)

- The same parametric studies have been repeated modeling cooling with HeII
- The heat transfer coefficient is that of the Bus Bar for the whole length considered

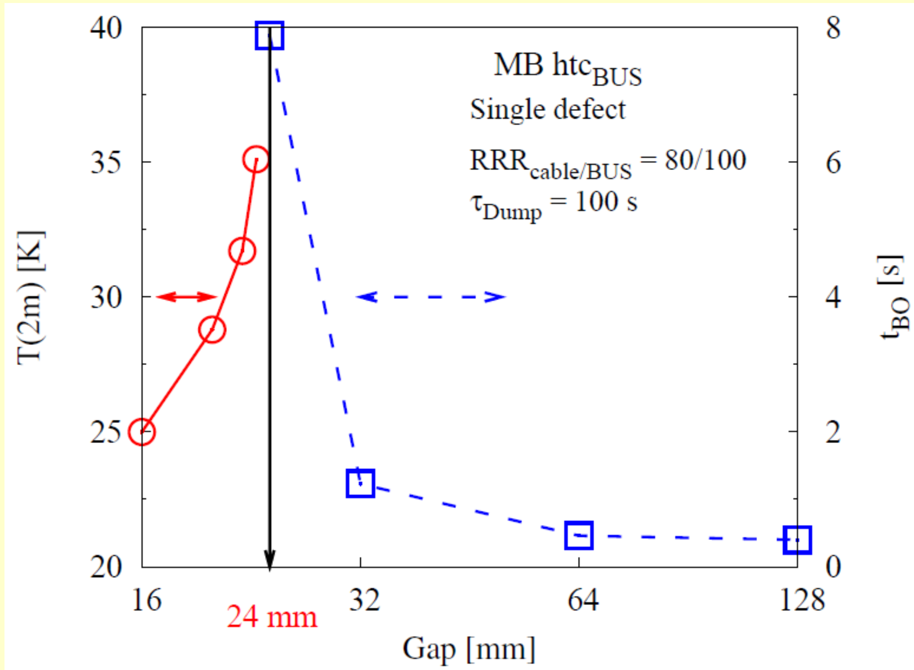


Heat Transfer to Helium Model Results (2/5)



In the stable cases the Bus Bar recovers to 1.9 K

The longer the defect the longer the recovery time

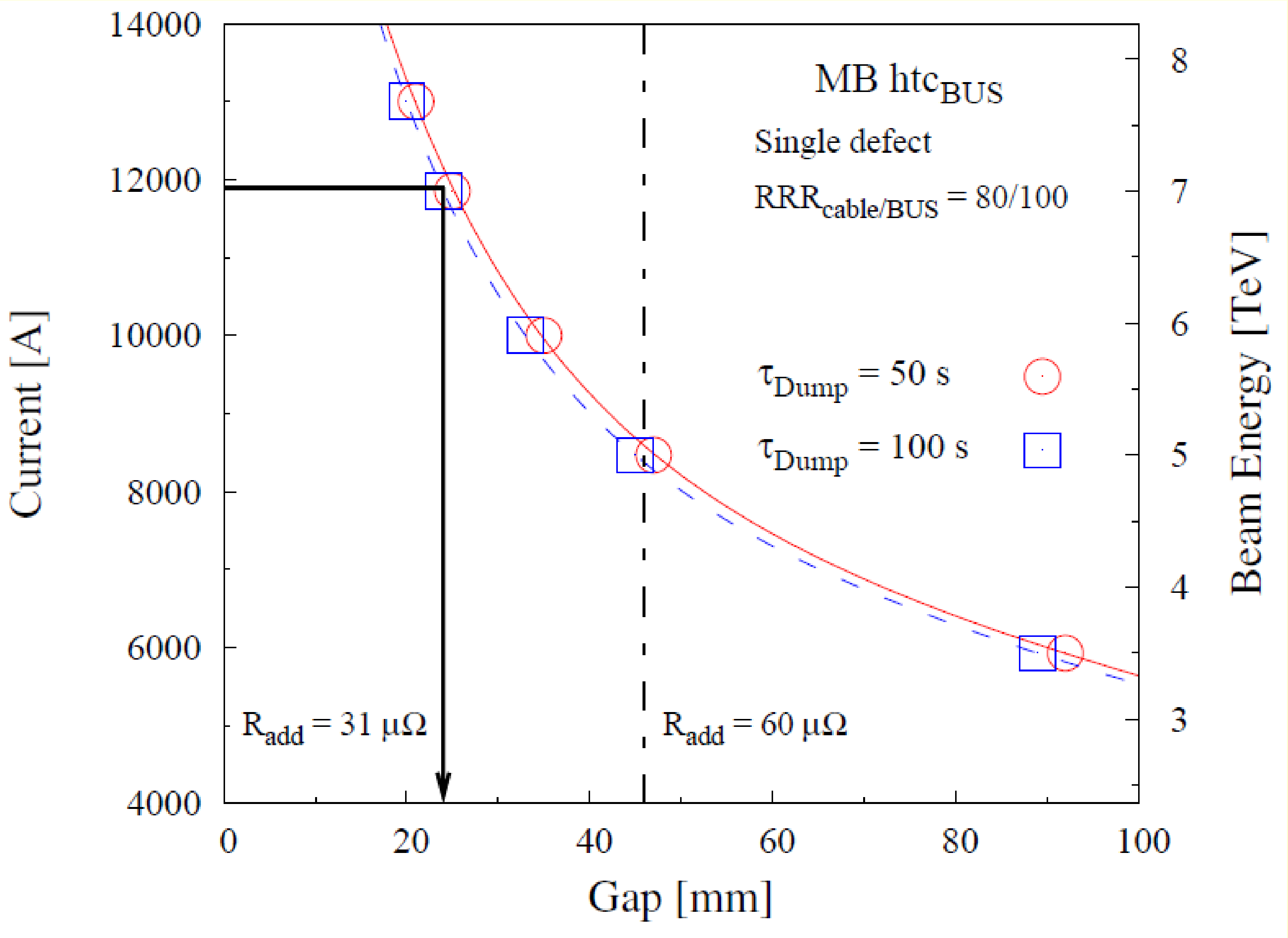


Critical gap: 24 mm

Burn out time ranges from 0.5 s to 8 s

Heat Transfer to Helium Model Results (3/5)

Stability as a function of the τ_{Dump}



The effect of the τ_{Dump} is negligible: short burn out time

Stability Improvement

3.5 TeV

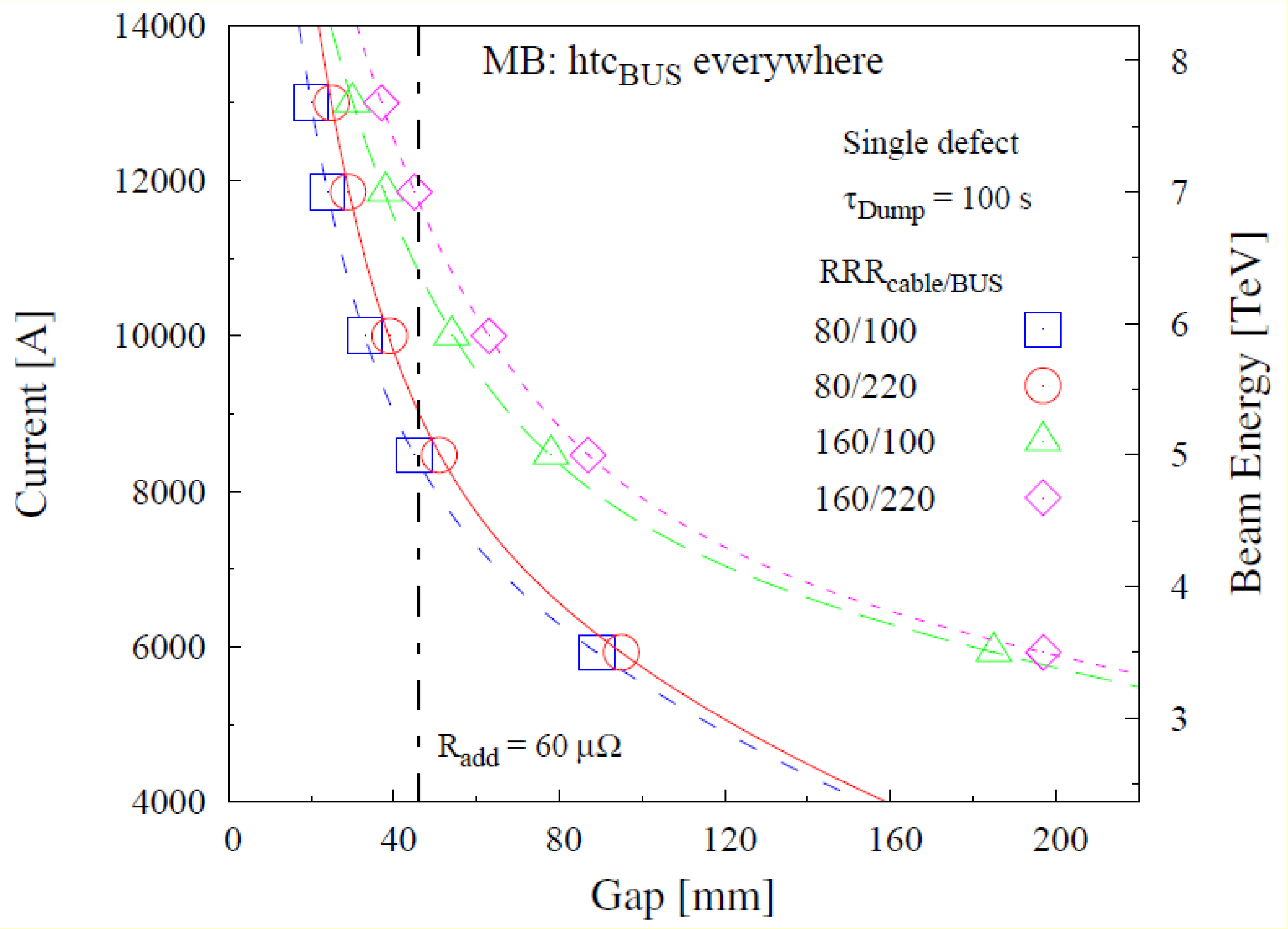
ΔR_{add} = 3.9 μΩ

4.0 TeV

ΔR_{add} = 3.9 μΩ

Heat Transfer to Helium Model Results (4/5)

Stability as a function of the *RRR*



With cooling the *RRR* is relevant:

improved longitudinal conduction favors heat extraction towards helium

Stability Improvement

3.5 TeV

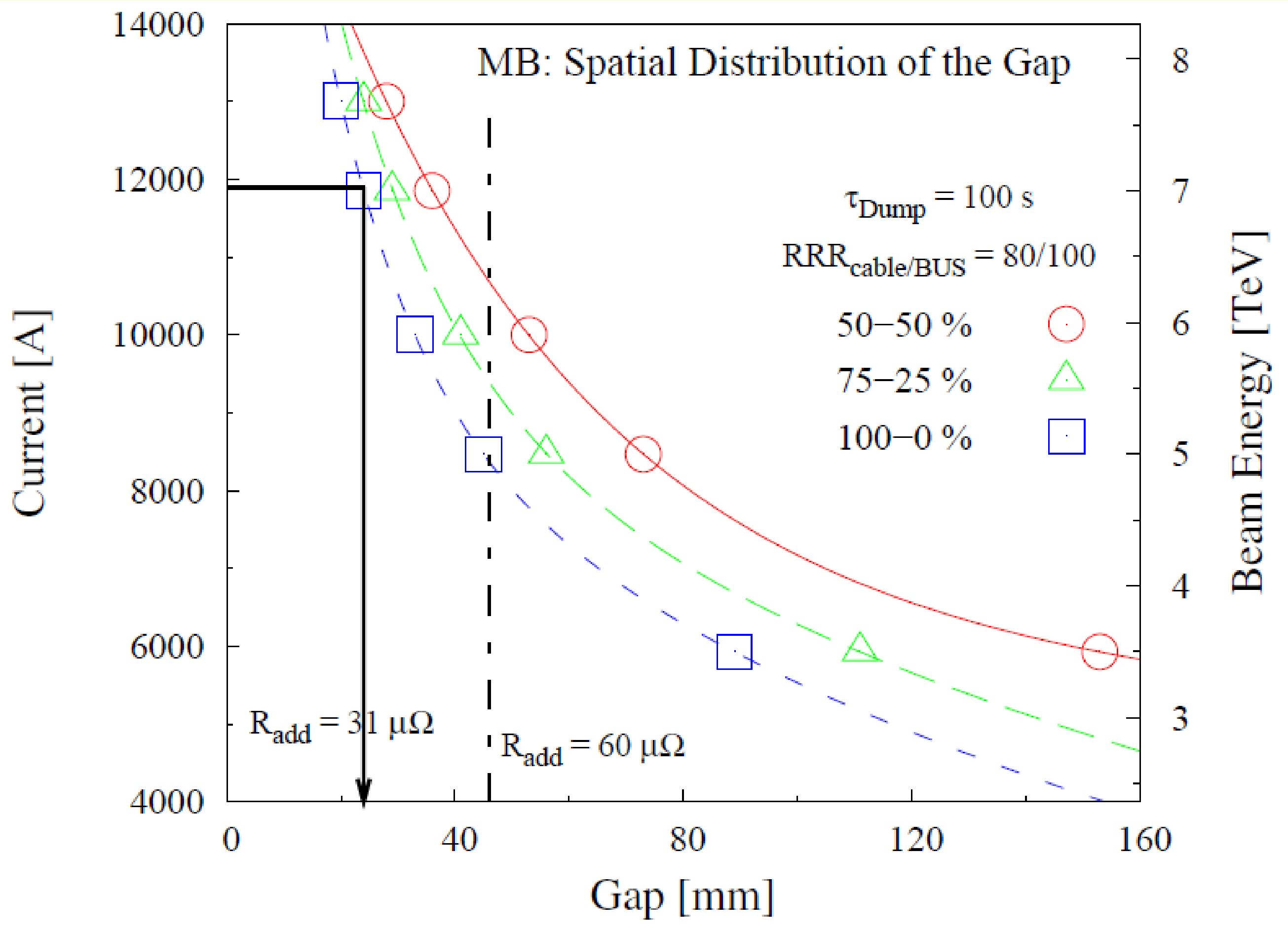
ΔR_{add} = 140.4 μΩ

4.0 TeV

ΔR_{add} = 96.2 μΩ

Heat Transfer to Helium Model Results (5/5)

Stability as a function of the *spatial distribution of the defect*



Stability Improvement

3.5 TeV

ΔR_{add} = 83.2 μΩ

4.0 TeV

ΔR_{add} = 55.9 μΩ

Summary I: Main Results of the Parametric Study

	Adiabatic	**vs.**	**Heat Transfer**
τ_{Dump}	Relevant effect		Limited effect due to short burn out times
RRR	Low impact for high currents Relevant impact for low currents		Relevant impact at all current levels due to an improved heat removal from the hot spot

The splitting of the defect significantly improves stability

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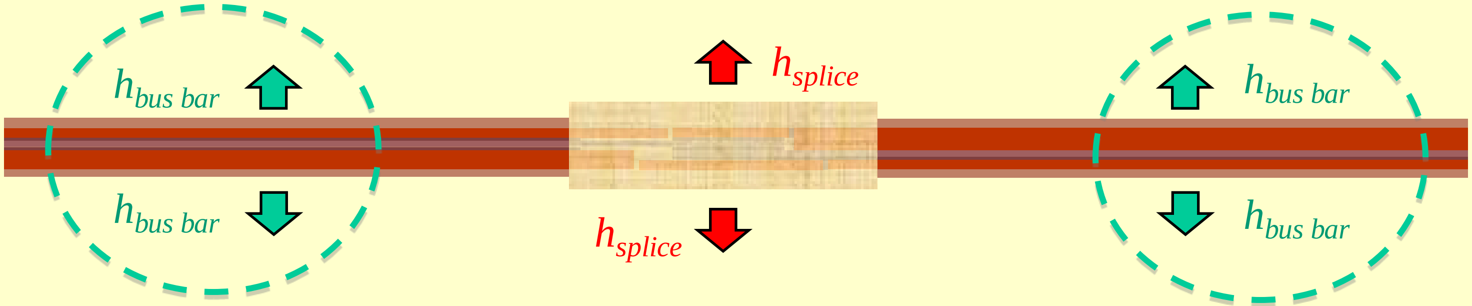
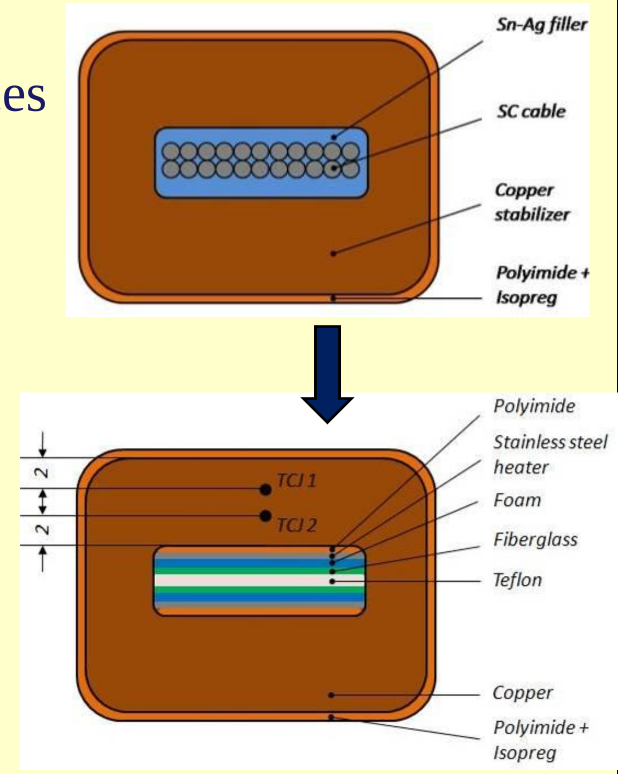
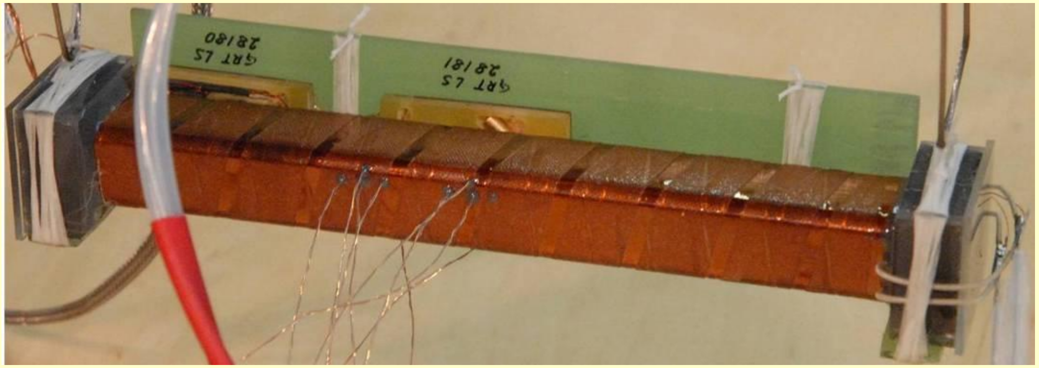


HT in the Bus Bar region: Experimental Analysis

- Sample: piece of (polyimide + ISOPREG) insulated MB bus bar instrumented with thermocouples, tested at 1.9 & 4.25 K, 0.1 MPa
- SC cable and Sn-Ag replaced with heaters & plastic pieces
- Max T limited by max drainable power from He bath
- Aim of the analysis: understand the long time constants, determine HTC & identify HT mechanisms → extend results to higher T

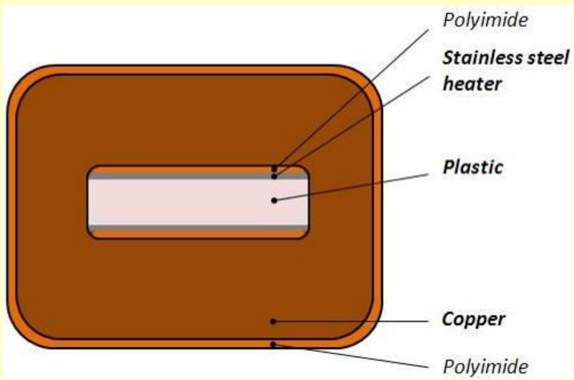


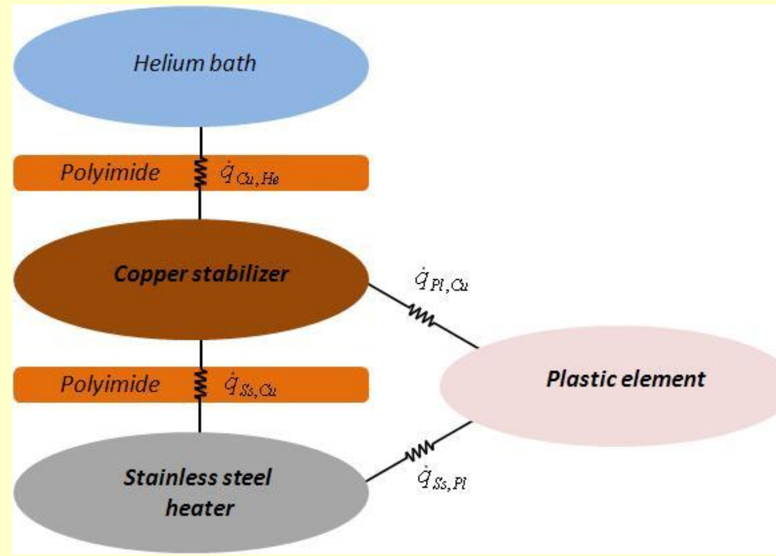


Measurements performed by D. Richter, TE-MSC

HT in the Bus Bar: Transient Analysis of the Tests

- 1-D THEA model with lumped parameters:
  - 3 thermal elements with T dependent properties
  - T dependent thermal resistances among them





- Heat balance equation solved for each component:

$$A_i \rho_i C_i \frac{\partial T_i}{\partial t} = \dot{q}'_i + \sum_{\substack{j=1 \\ j \neq i}}^{3} \frac{p_{ij}}{\delta_{ij}} \int_{T_i}^{T_j} k_{ij}(T)\,dT - p_{ih} h_{ih} (T_i - T_h) - Q_{HeII}$$

Heat capacity

Conduction heat transfer btw components

Heat deposit in heaters

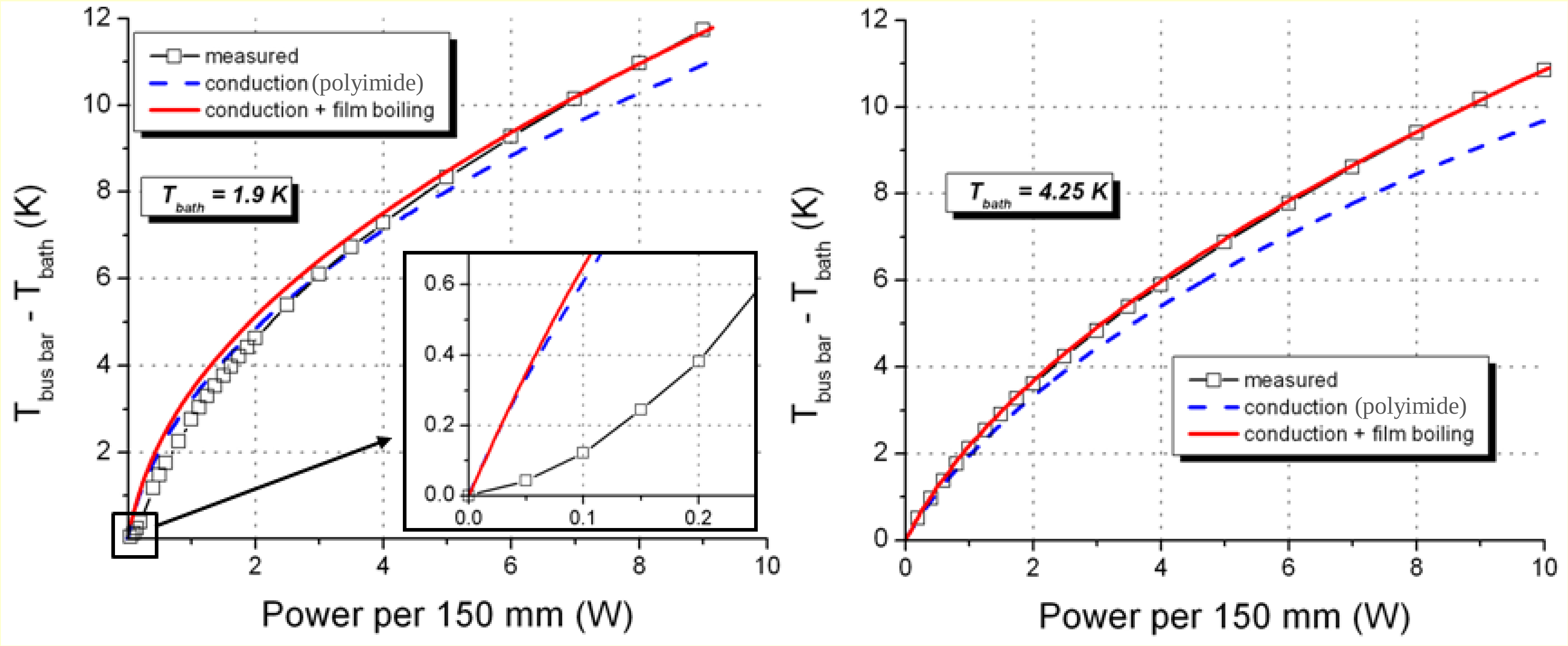
Heat transfer btw bus bar and 1.9 K He bath

h_{ih}:

- *conduction below critical heat flux (CHF)*
- *conduction and film boiling above CHF*

HT in the Bus Bar: Steady-State Analysis of the Tests

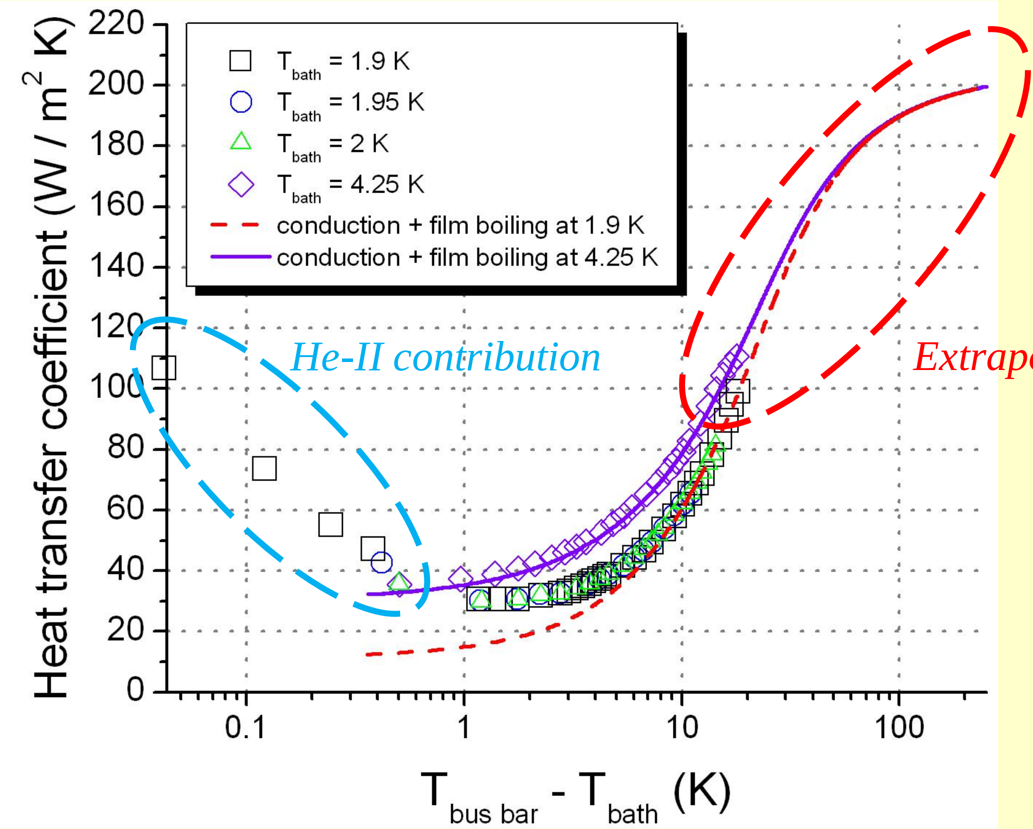
- Superfluid helium contribution, through μ-channels insulation, for low ΔT



- Film boiling formation limits the heat extraction through the insulation bulk solid conduction:
  - from ΔT of ~ 10 K in He-II & from very low ΔT in He-I bath

HT in the Bus Bar region: Heat Transfer Coefficient

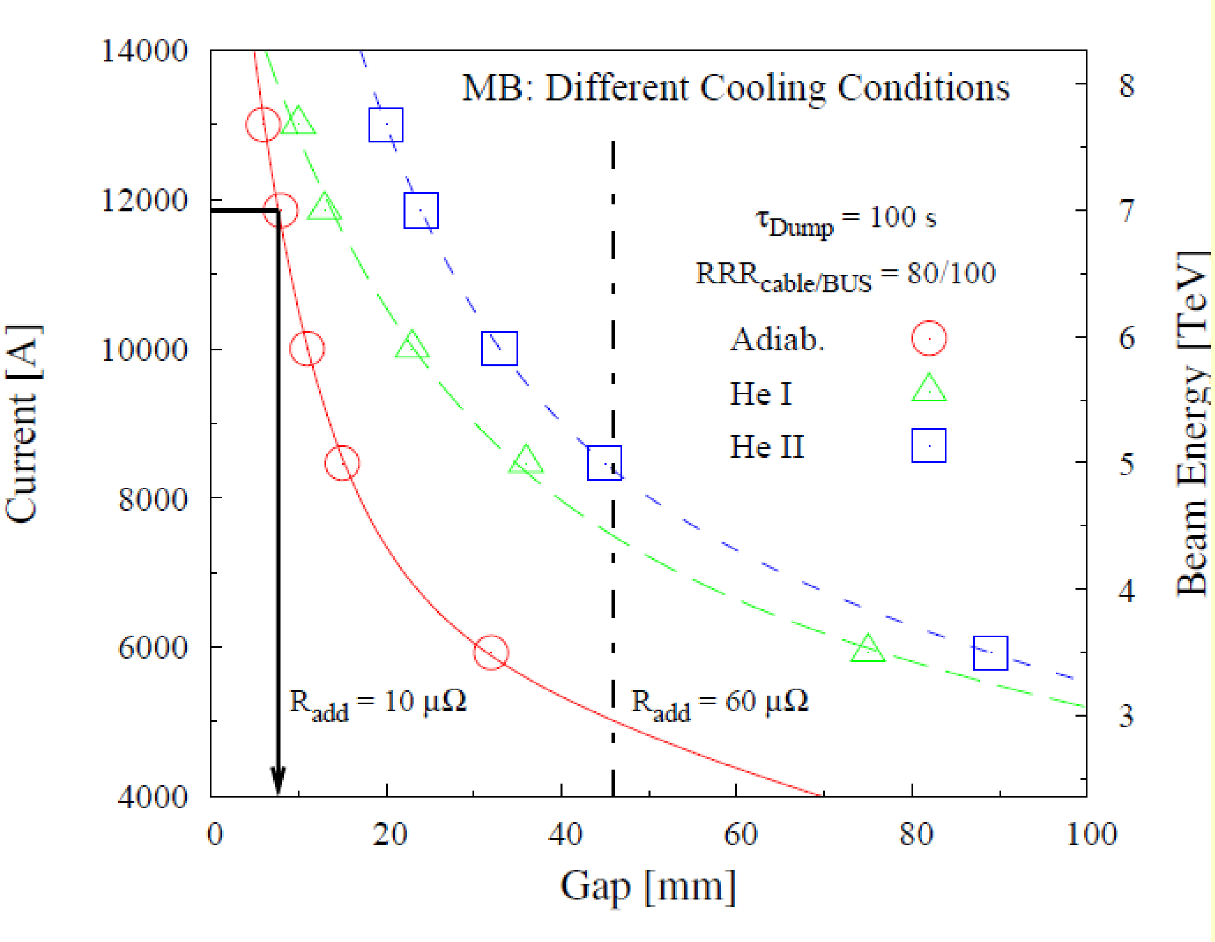
- MB and MQ bus bar heat transfer coefficient:



- Results extended above the maximum measured temperature

Stability dependence on the Bus Bar HT mechanisms

- Stability dependence on the bath Temperature:



$R_{additional}$ [μΩ]	3.5 TeV (τ_{dump}: 100 s)	7 TeV (τ_{dump}: 100 s)
Adiabatic everywhere	*42*	*10*
He-I	*97.5*	*17*
He-II	*116*	*31*

Increase of the acceptable R_{add} by a factor of 2-3 !

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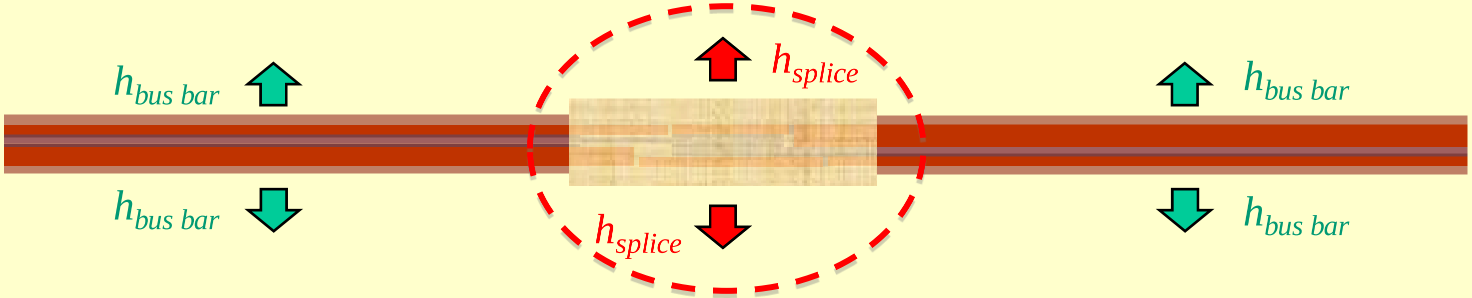
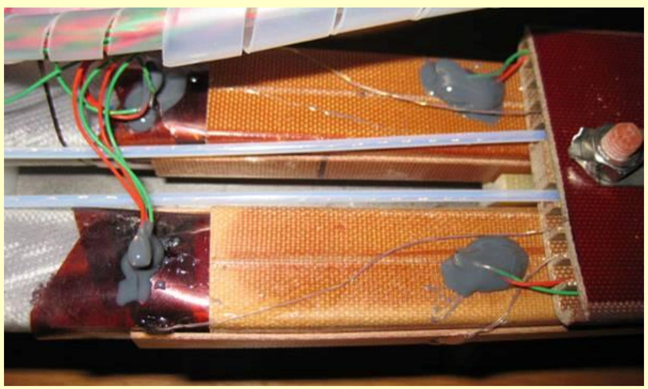
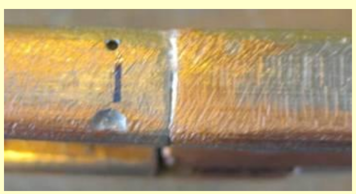
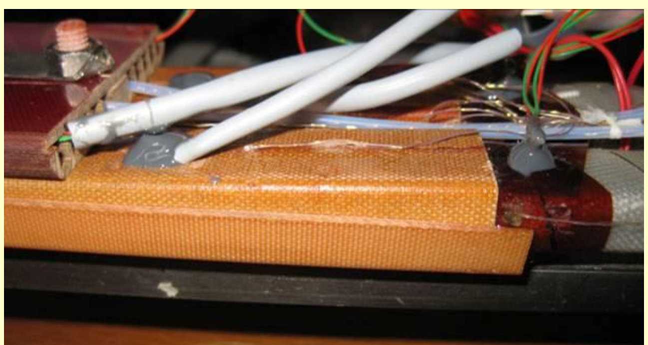


FRESCA Experimental Analysis of Defective Interconnections (IC) (1/2)

- Defective ICs were experimentally investigated in FRESCA
  - Sample 2b: MQ IC with one-side defect, 35 mm long
- Initial investigation of thermal tests in He-I bath with no current



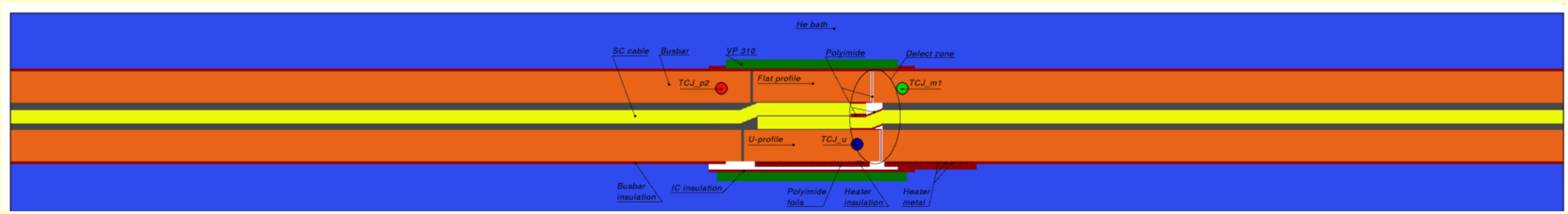


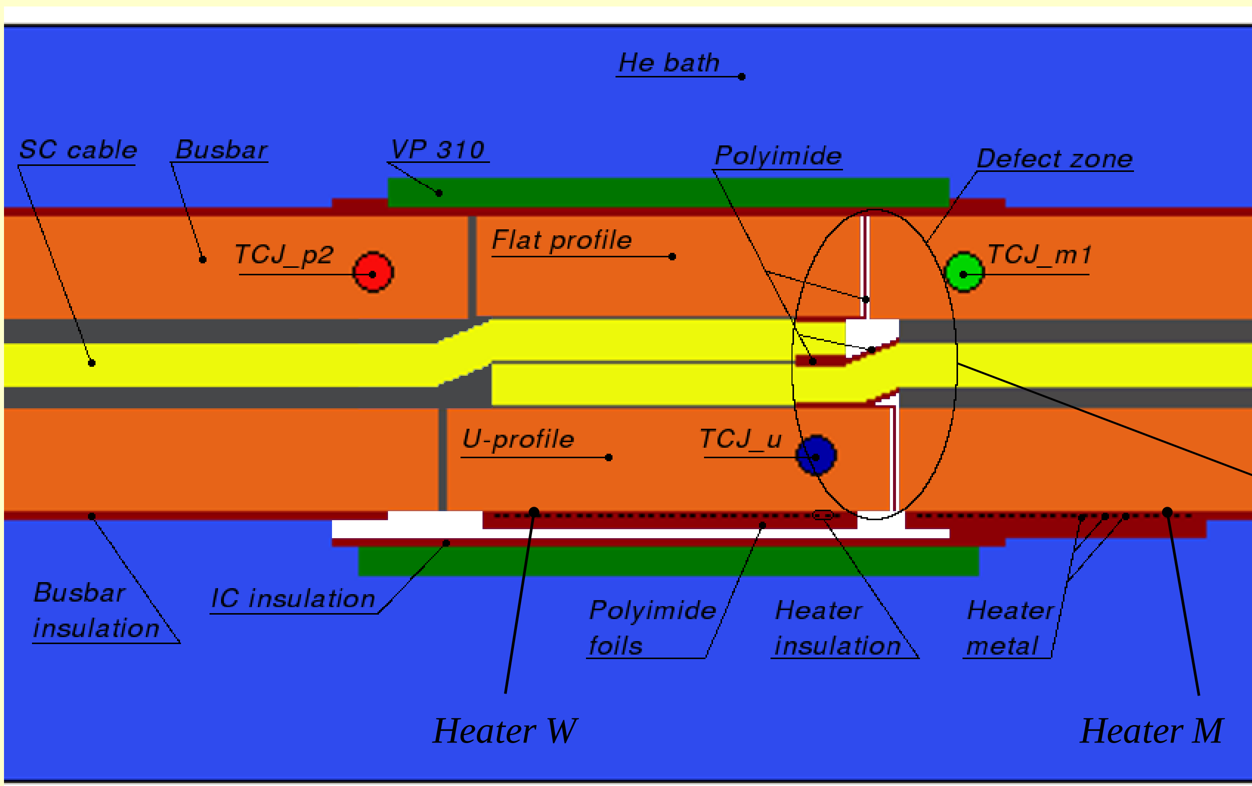


Pictures courtesy of G. Willering, TE-MSC

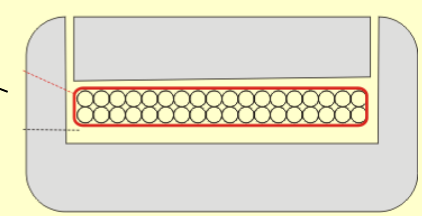
FRESCA Experimental Analysis of Defective IC (2/2)

- Scheme of the experimental setup:



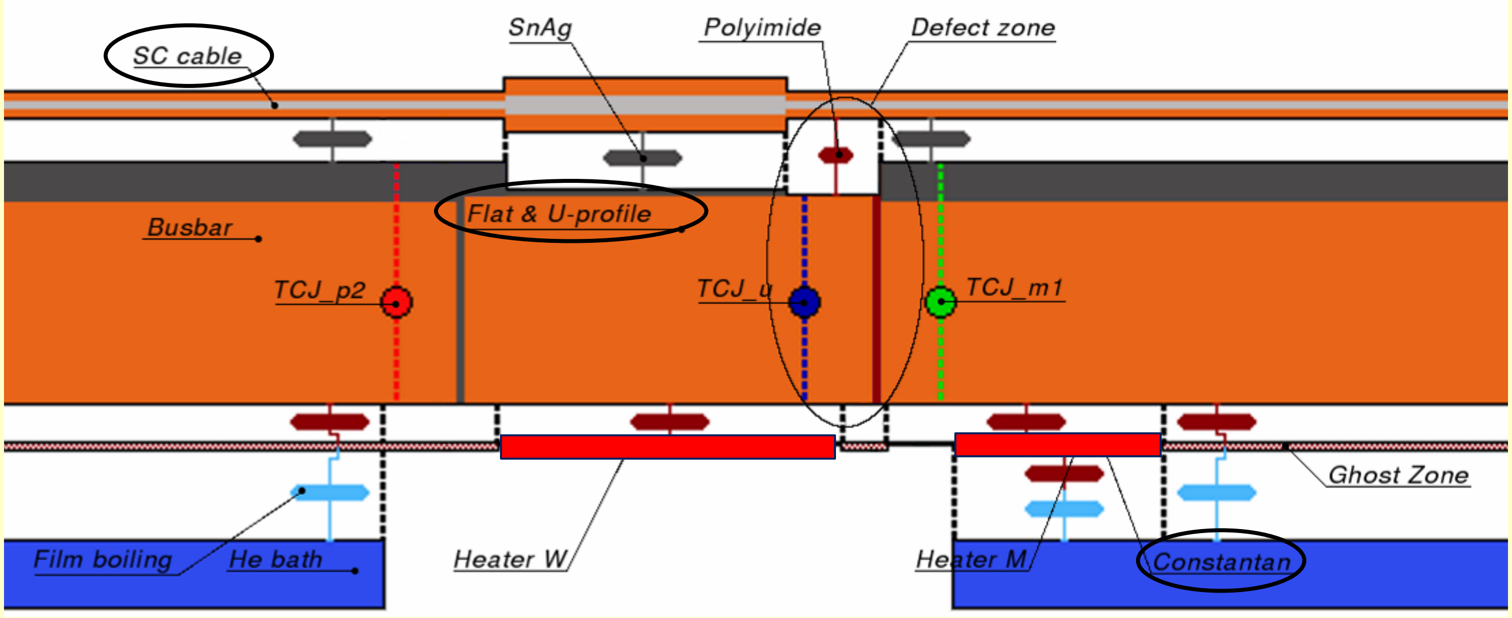


- No connection between:
  - SC cable and Bus Bar
  - Bus Bar and U/Flat-profiles



Model description

- Developed THEA model:
  - Heat balance equations for 3 thermal elements linked through Temperature dependent thermal resistances (SnAg, Polyimide, Fiberglass, He)
  - Test parameters implemented (geometry, RRR)
  - **Adiabatic Interconnection**



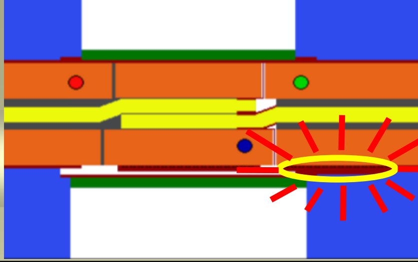
Thermal elements:

1) SC cable

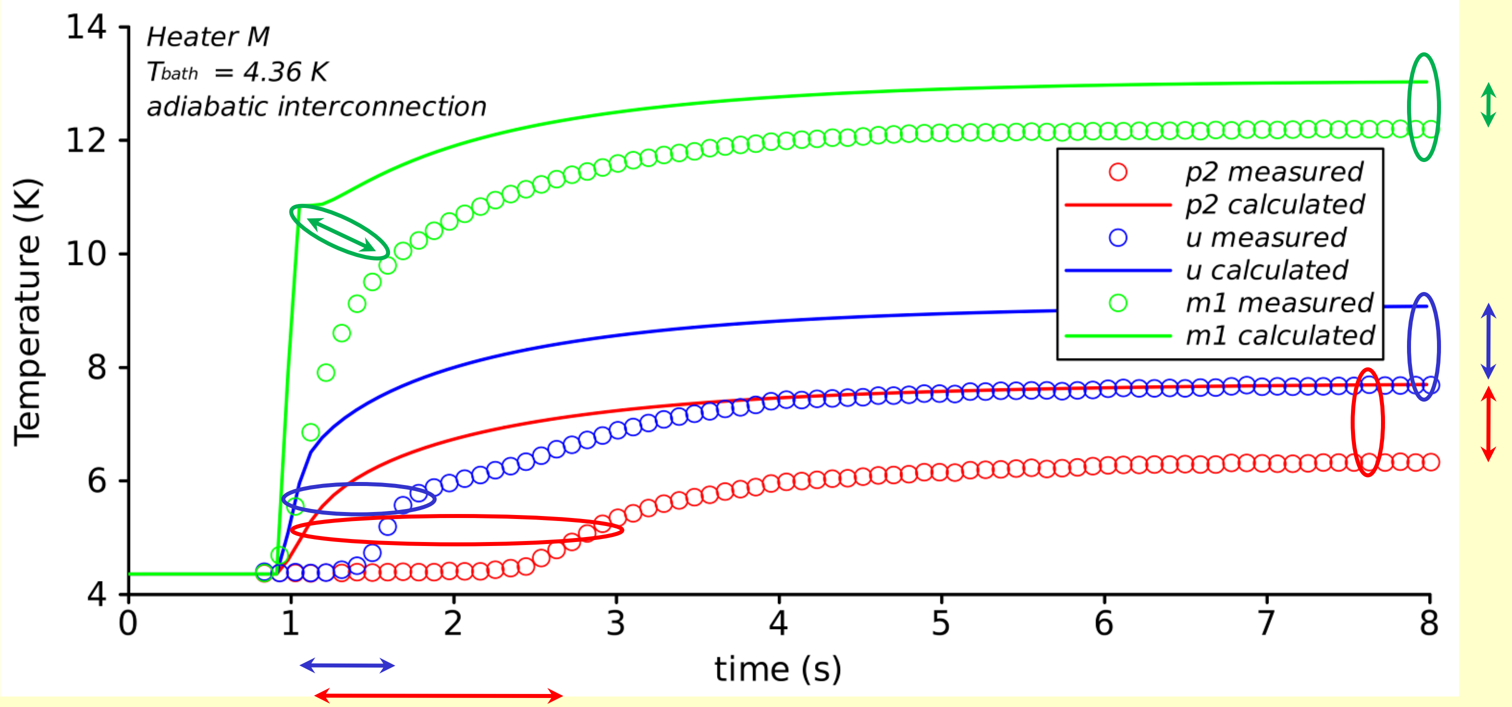
2) Bus Bar

3) Heaters

Results with Adiabatic IC

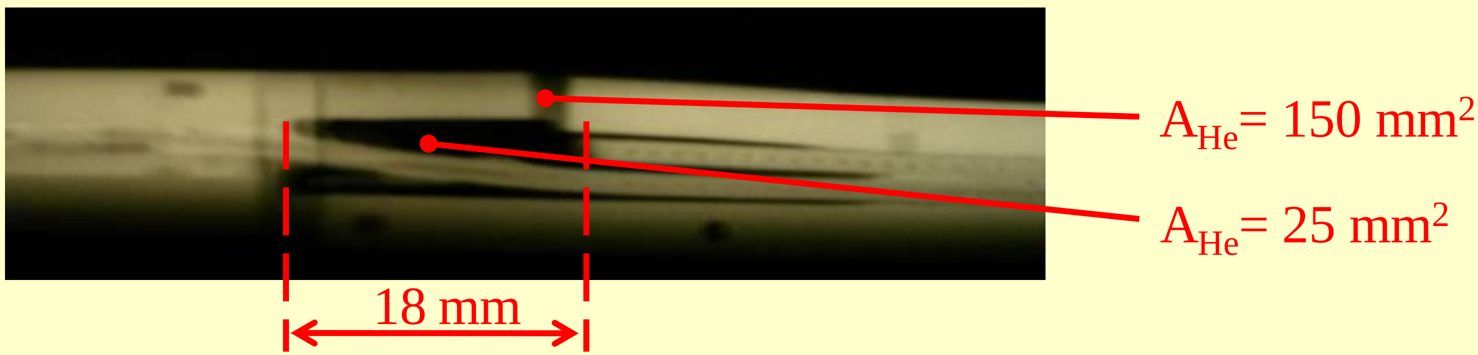


- Heater M turned on
- This model does not catch the features of the measurements:
  - Steady state temperatures, time delays, transient states

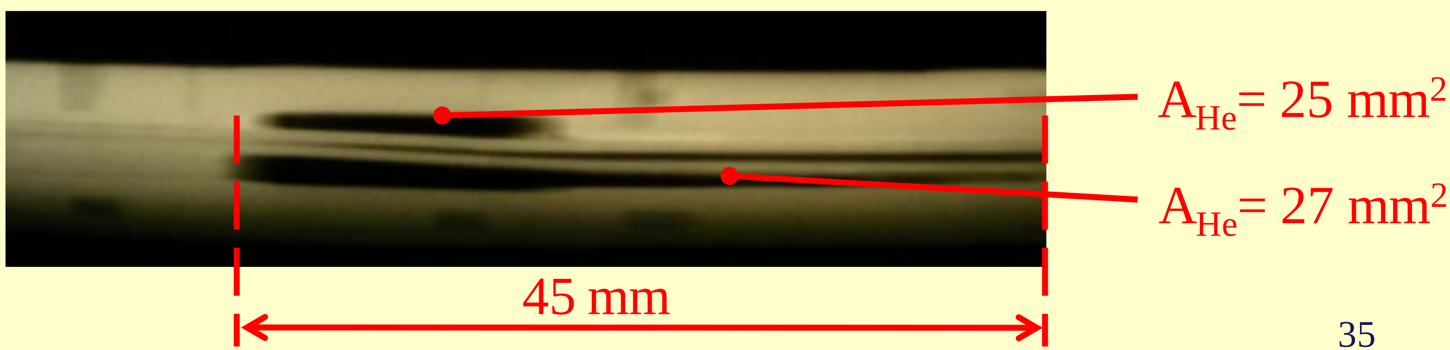


Is He filling the voids in the IC / bus bar ?

- A helium reservoir could be present inside the IC and Bus Bar
- γ-ray pictures:
  - Defective side of the IC



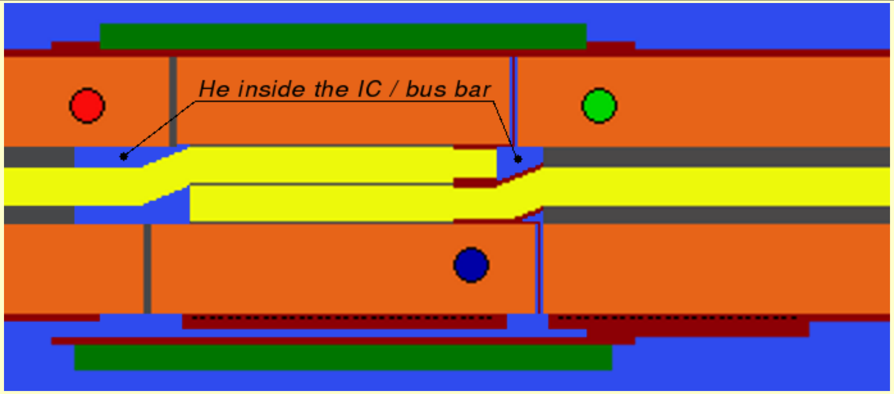
  - Good side of the IC

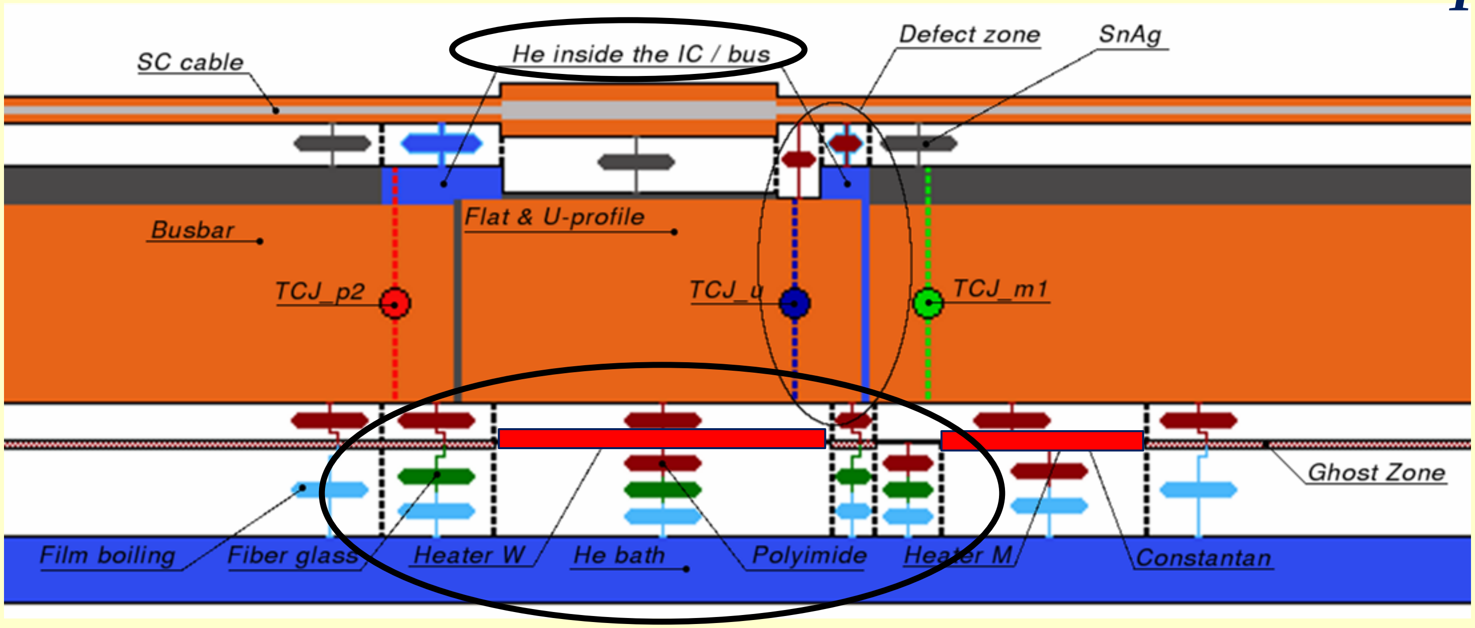


Model with He inside the IC / bus bar

- **Complete model:**
  - **- non adiabatic splice**

    solid conduction through polyimide and fibreglass considered, as well as film boiling
  - **- with He in the IC/bus**

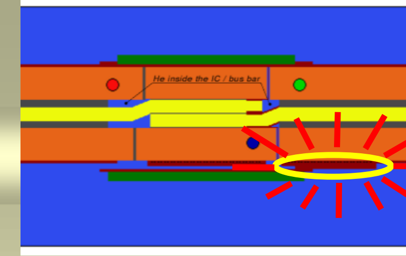




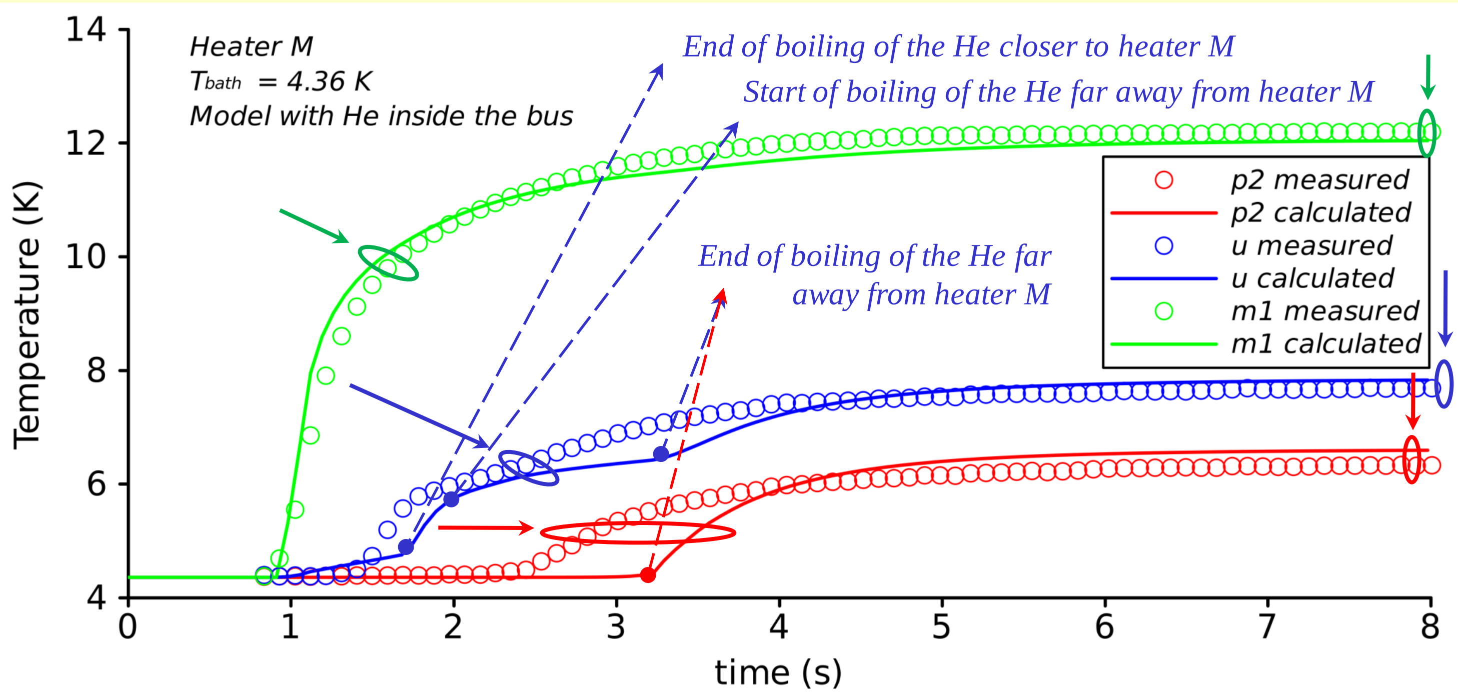
Thermal elements:

1) *SC cable*
2) *Bus Bar*
3) *Heaters*

Results with He inside IC/bus



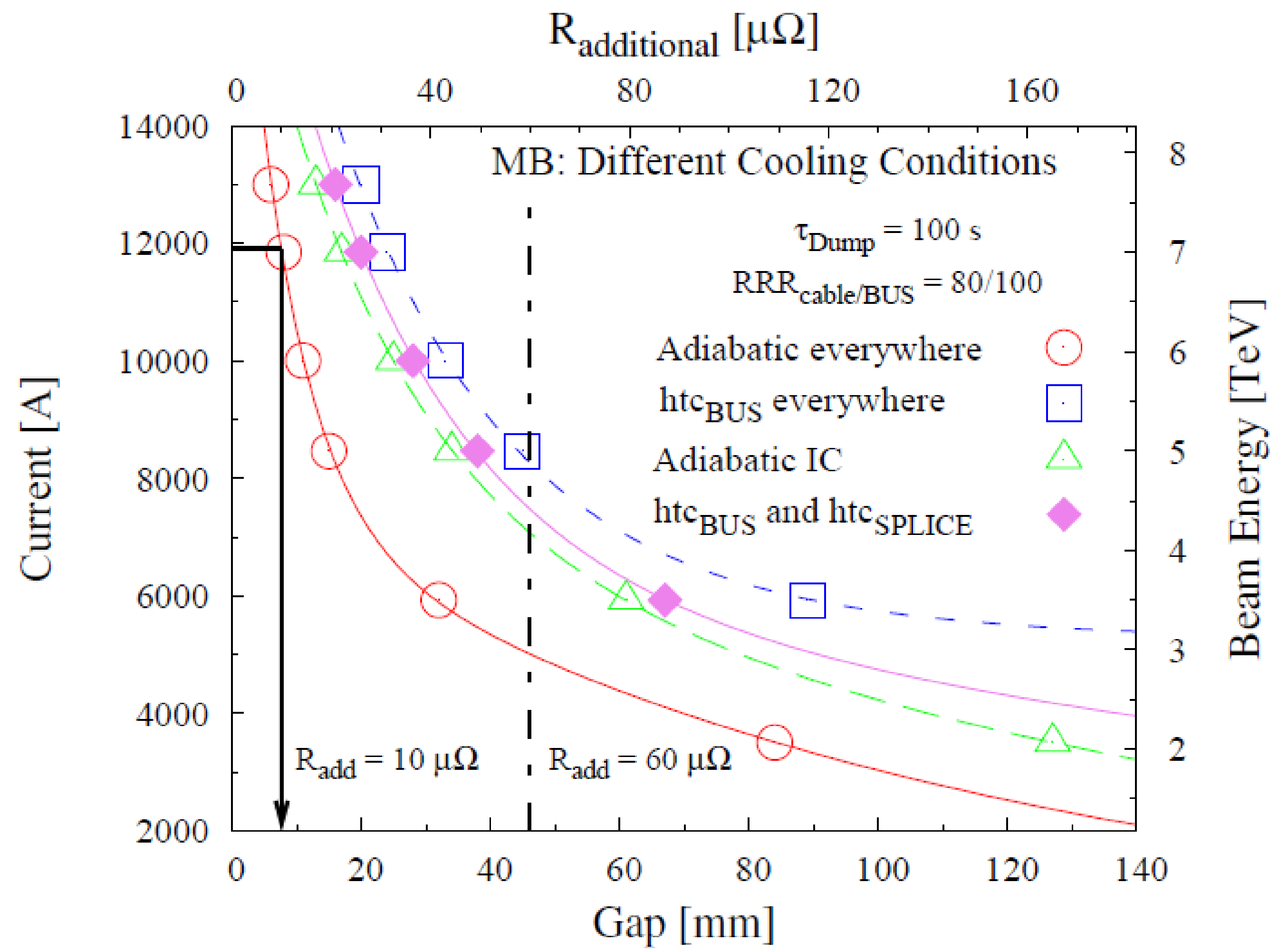
- Heater M turned on: Good agreement with experimental results
  - steady-state Temperatures are correct within 0.35 K → the IC is not adiabatic
  - initial delays and transient features are reproduced by the He inside IC and bus

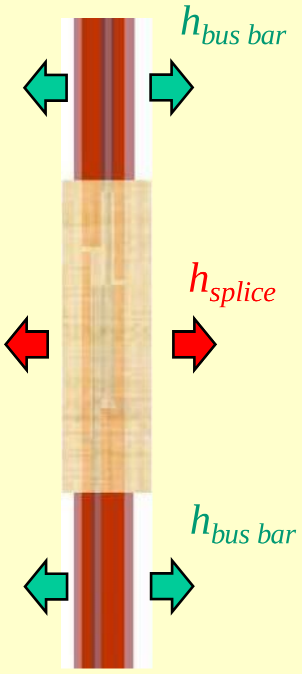


- changes of slope of the calculated curve are associated to boiling of the He inside IC/bus

Stability dependence on IC HT mechanisms (1/2)

- Stability dependence on the IC Heat Transfer behavior :





Conservative hypothesis on:

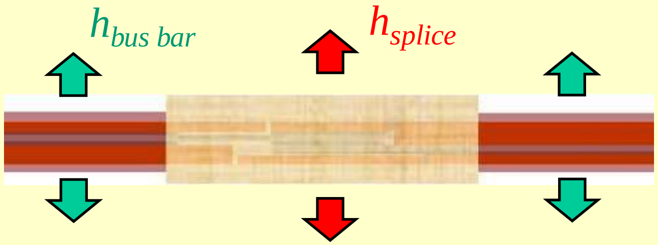
- *Cable and bus bar RRR*
- *no He inside the IC*
- *no He-II contribution in the IC*

Stability dependence on IC HT mechanisms (2/2)

➢ Best estimate of safe operating conditions:

$R_{additional}$ [μΩ]	3.5 TeV τ_{dump}: 50 s	4 TeV τ_{dump}: 50 s	4 TeV τ_{dump}: 68 s	7 TeV τ_{dump}: 100 s
Adiabatic everywhere	*56*	43	38	*10*
Adiabatic IC	*82*			*22*
Bus htc & IC htc	*90*	71.5	71.5	*26*
Bus htc everywhere	*120*			*31*

Higher cable & bus RRR, He-II effect in the IC…



Conservative hypothesis on:

- *Cable and bus bar RRR*
- *He inside the bus (no contact with bath)*
- *no He-II contribution in the IC*

Heat Transfer provides an increase of the acceptable R_{add} by a factor of at least ~ 2 !

Summary II: Heat Transfer and Impact on Stability

- The heat transfer mechanisms in the bus bar and IC were investigated
  - through dedicated bus bar thermal measurements:
    - *He-II effect at low T, film boiling formation at high T*
  - by analyzing the FRESCA experiments on defective IC:
    - *non adiabatic behaviour*
    - *presence of He inside the IC / bus bar*

- The impact of the local heat transfer on the IC stability was assessed:
    - *it provides an increase of the acceptable* R_{add} *by a factor of at least* ~ 2
    - *MB at* 4 TeV (τ = 50 *or* 68 s)*: unstable* R_{add} > 71.5 μΩ
    - *more margin available, thanks to IC heat transfer (to be evaluated)*

Perspectives

- Complete the analysis of the FRESCA tests in terms of local heat transfer:
  - *in He-II bath*
  - *with current*
  - *also considering other defects (2-sides, etc…)*

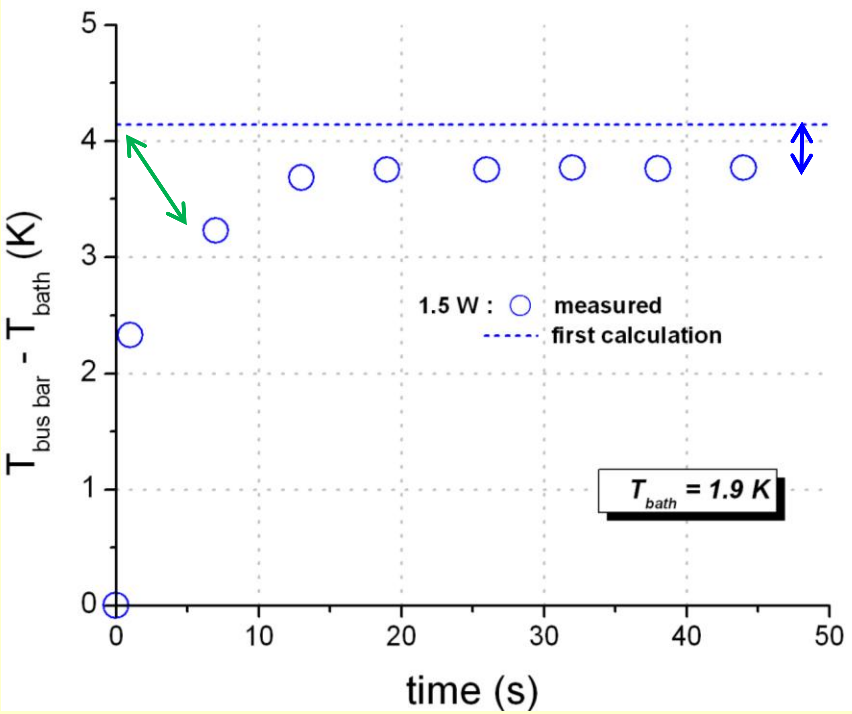
- Derive the IC heat transfer

- Reduce the uncertainty on the stability curves, thus providing the margin that is still available

- Apply the developed model to shunted IC

HT in the Bus Bar: Transient Analysis of the Tests (2/3)

- The measured curve can be reproduced acting on two parameters:

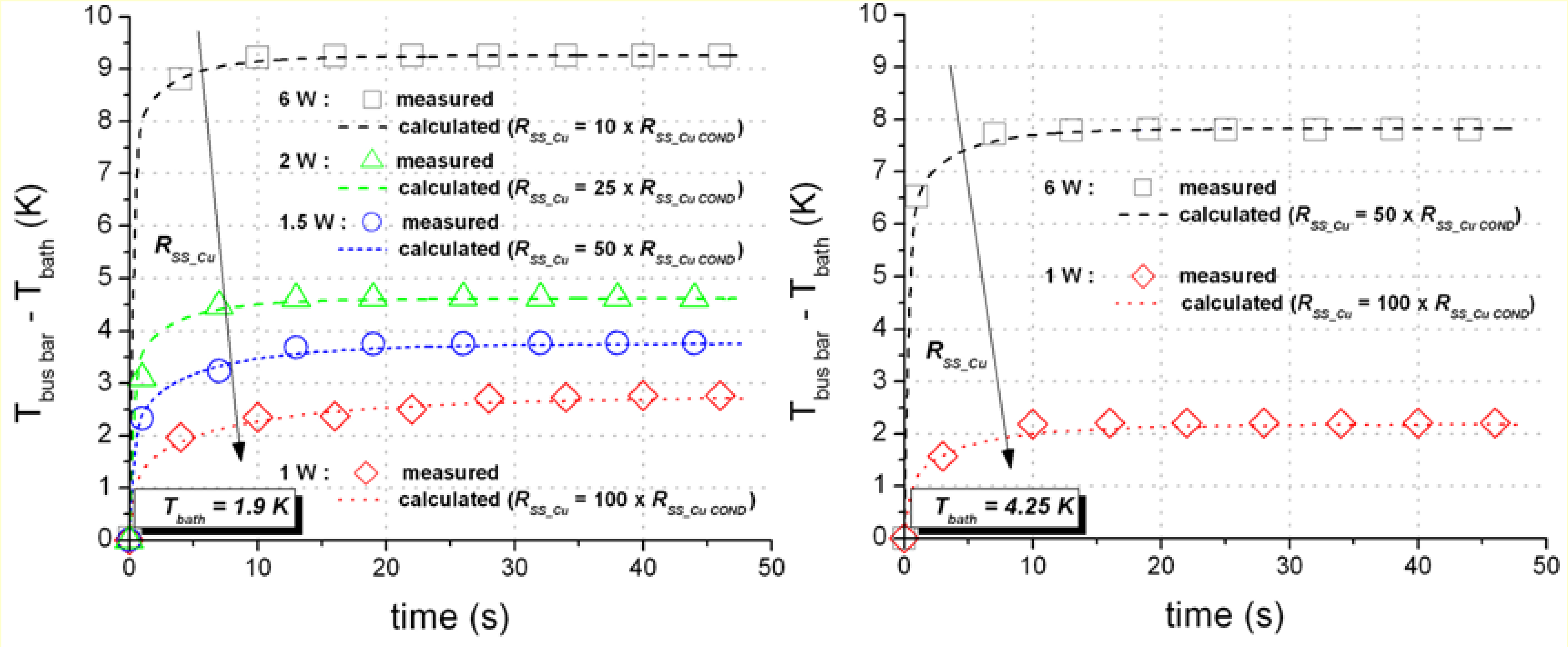


1) Thermal resistance btw heaters & bus bar R_{SS_Cu} :
   - Impact on the transient process
   - Limited heat transfer (T_{SS} ↑, T_{Cu} ↓) → increasing with time

2) Contribution of superfluid helium:
   - Impact on the steady-state temperature
   - Through the μ-channels between the insulation tapes

HT in the Bus Bar: Transient Analysis of the Tests (3/3)

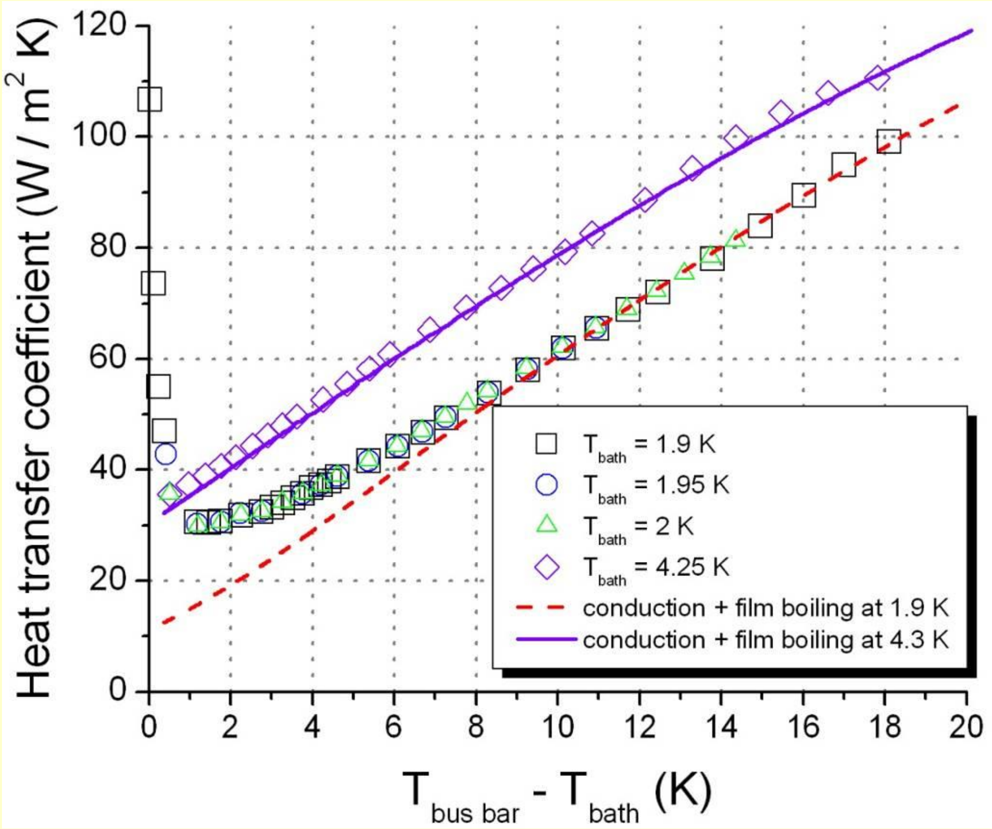
➢ The high thermal resistance btw heaters and bus bar due to differential thermal contractions between bus bar and pieces filling the hole



➢ The lower the T, the larger the detachment between bus bar and pieces filling the hole, the higher R_{SS_Cu}

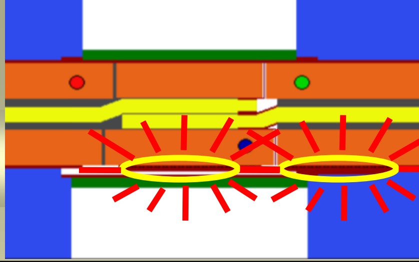
HT in the Bus Bar region: Heat Transfer Coefficient

- MB and MQ bus bar heat transfer coefficient:

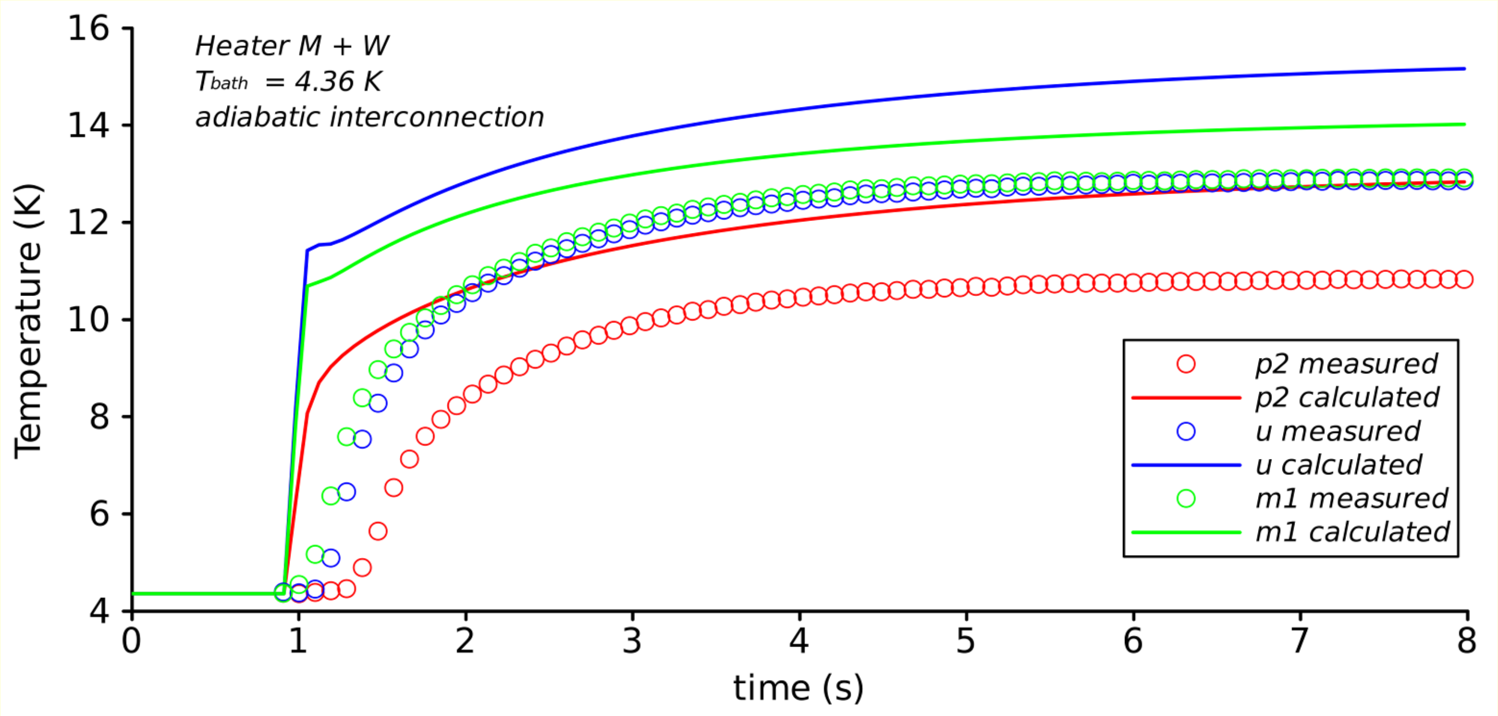


- Results extended above the maximum measured temperature

Results with Adiabatic IC (2/2)

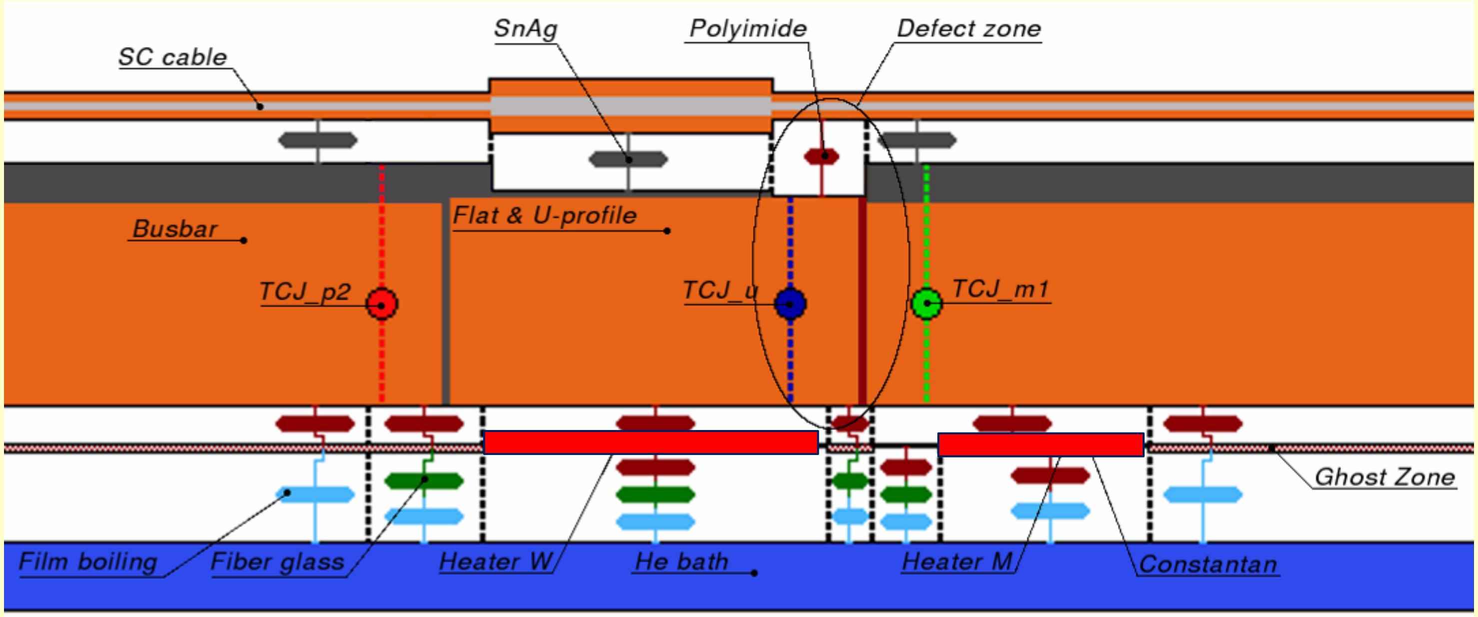


- Heaters M and W turned on
- This model does not catch the features of the measurements:
  - Steady state temperatures, time delays, transient states



Implementation of a Non Adiabatic IC

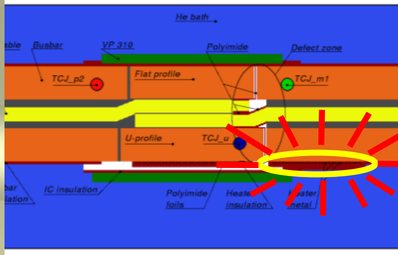
- Model with **non adiabatic interconnection**:
  - solid conduction through polyimide and fiberglass considered, as well as film boiling



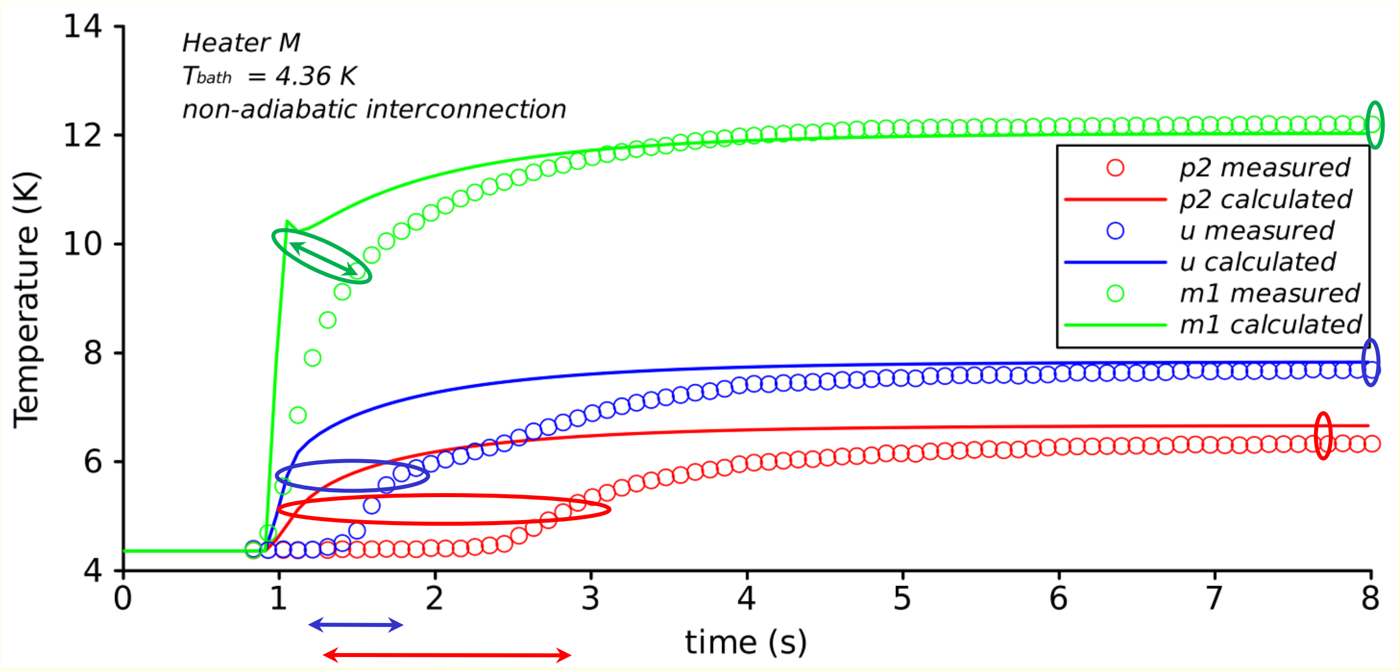
Thermal elements:

1) *SC cable*
2) *Bus bar*
3) *Heaters*

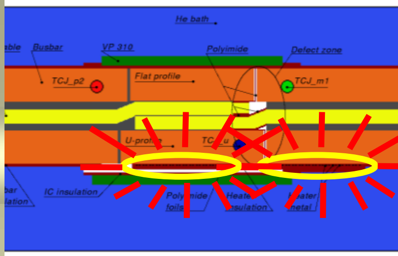
Results with Non Adiabatic IC (1/2)



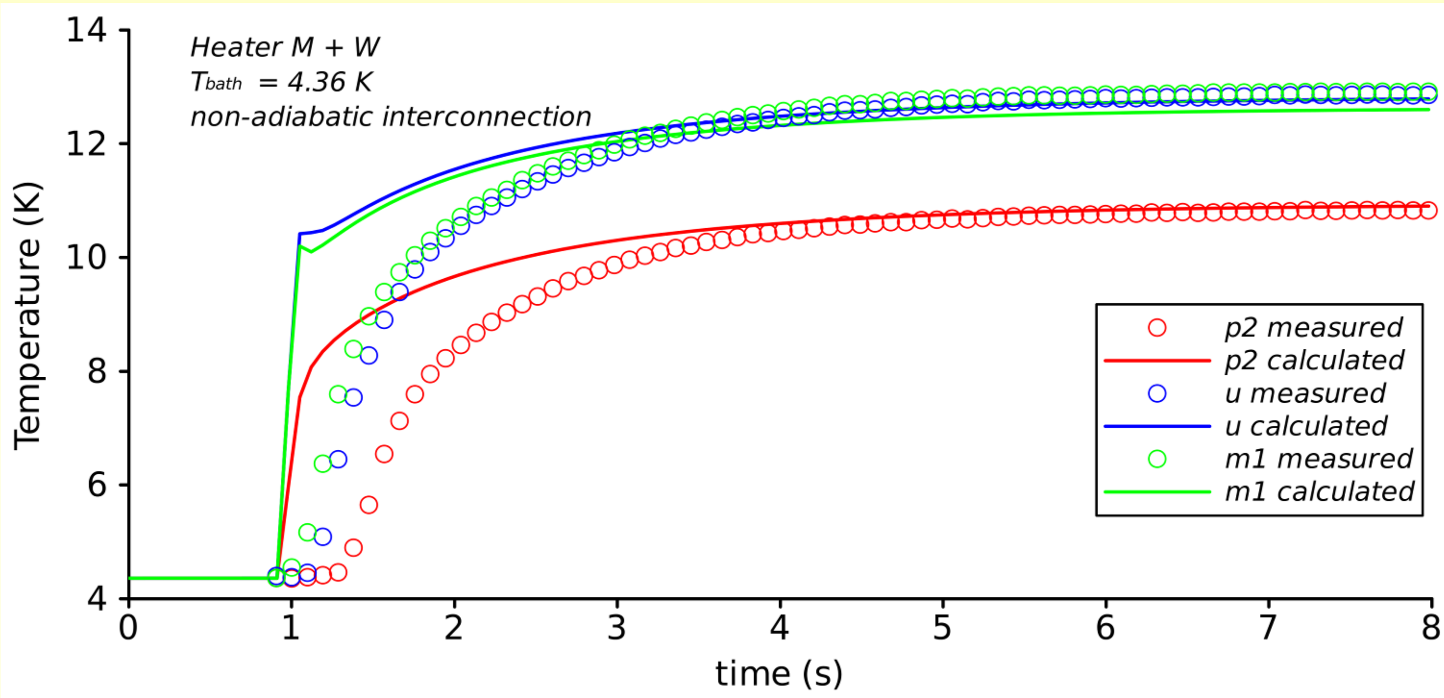
- Heater M turned on:
- The steady-state Temperatures are correct within 0.35 K
  - the IC is therefore not adiabatic
- The initial delays and transient features are not reproduced by the model



Results with Non Adiabatic IC (2/2)



- Heaters M and W turned on:
- The steady-state Temperatures are correct within 0.3 K
  - the IC is therefore not adiabatic
- The initial delays and transient features are not reproduced by the model



Implementation of He inside the IC / bus bar

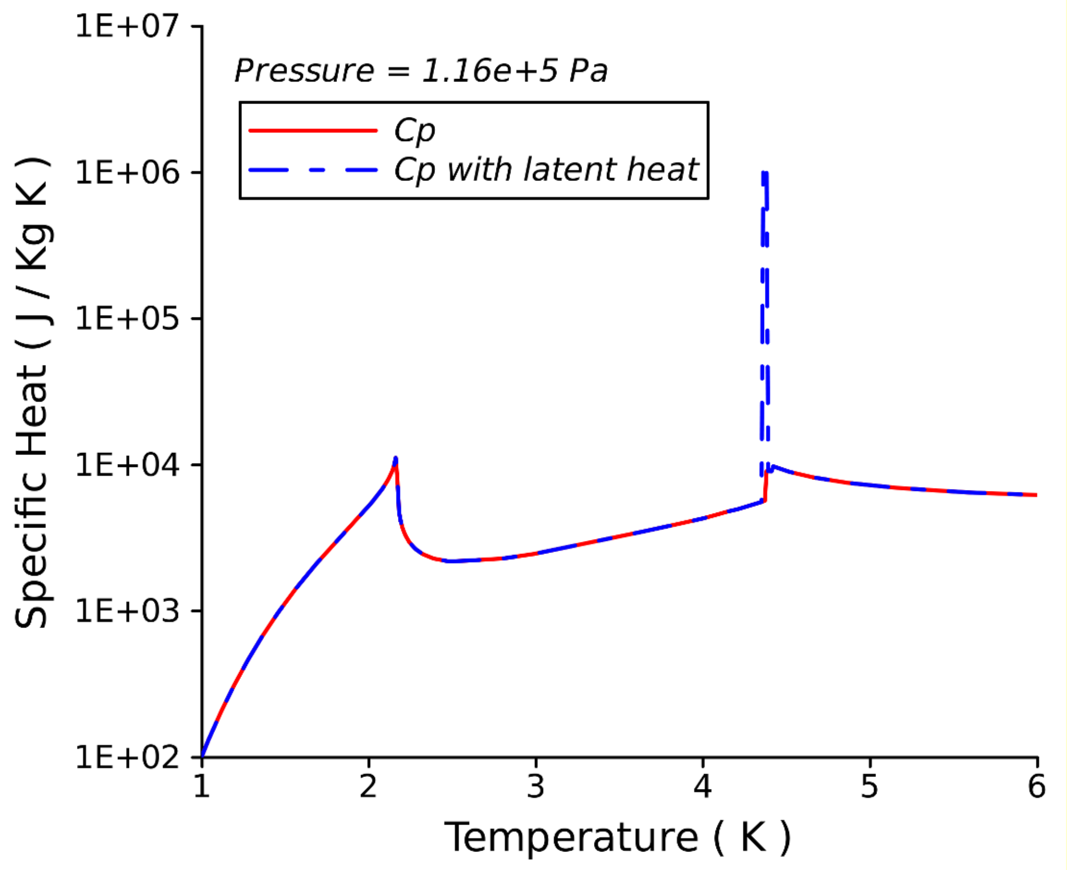
- The latent heat of vaporization is taken into account in the definition of specific heat :

constant pressure => dH = dQ

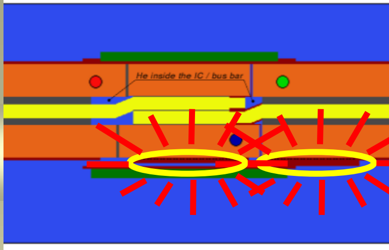
$$\frac{\int_{T_1}^{T_2} \frac{dH}{dT} dT}{(T_2 - T_1)} = \frac{\int_{T_1}^{T_2} \frac{dQ}{dT} dT}{(T_2 - T_1)}$$

$$\frac{(H_2 - H_1)}{(T_2 - T_1)} = Cp_{av}[T_1, T_2]$$

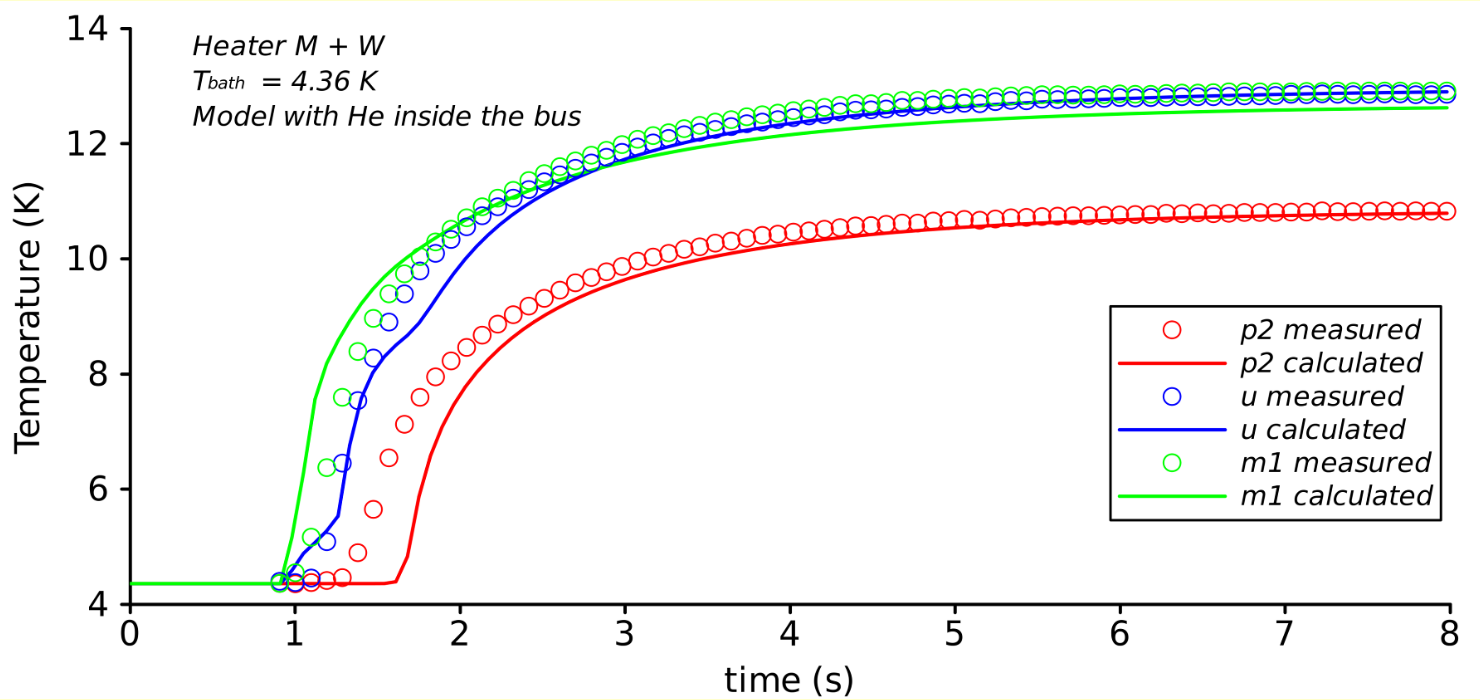
$$T_1 = 4.36 \text{ K}, \ T_2 = 4.38 \text{ K}$$



Results with He inside IC/bus (2/2)

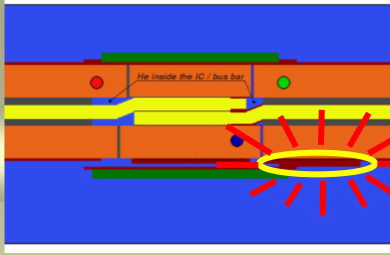


- Heater M and W turned on: Good agreement with experimental results

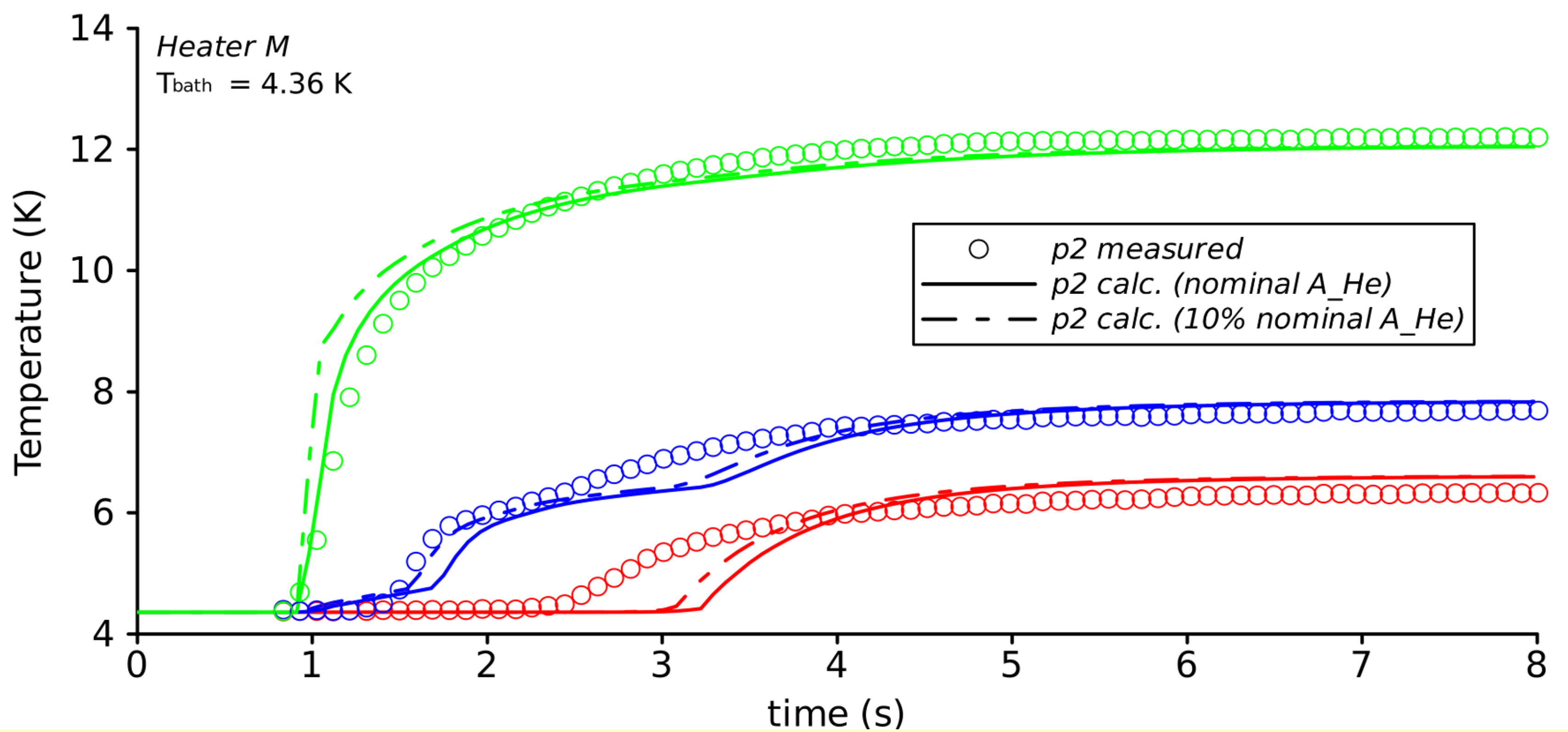


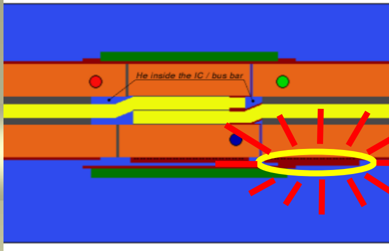
- Even small quantity of He inside the IC / Bus (10% of void cross section) has a significant impact on transient

Results with He inside IC/bus (3/3)



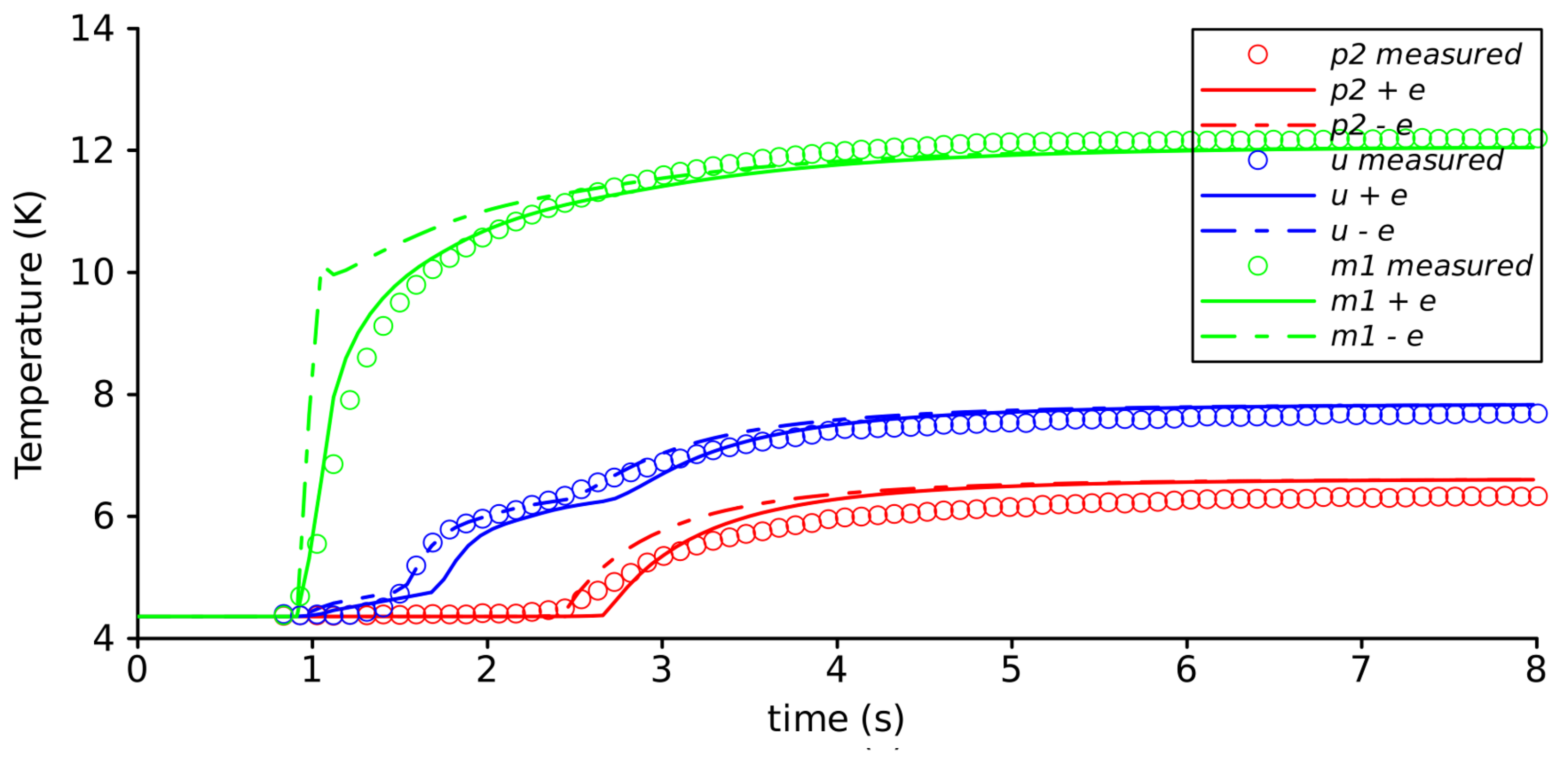
- Heater M turned on:
  - small quantity of He inside the IC / Bus (10% of void cross section) has a significant impact on transient



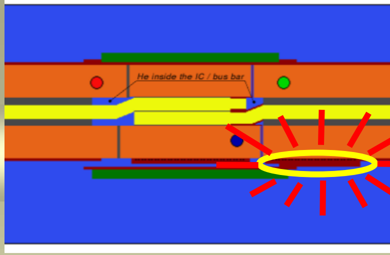


Results with He inside IC/bus (4/4)

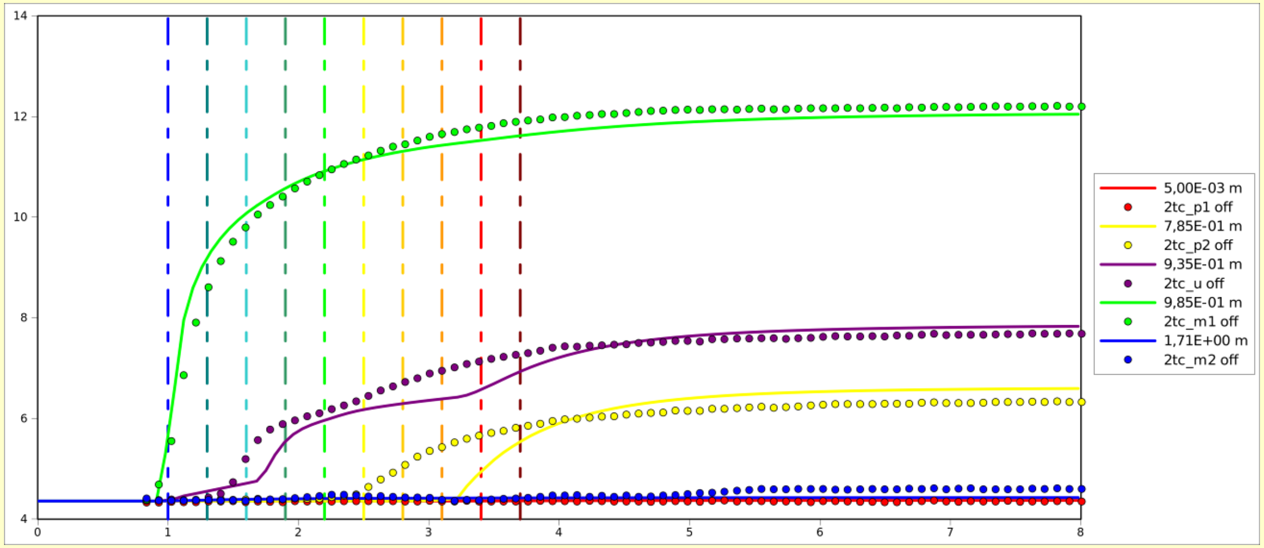
- Heater M turned on:
  - impact of the length of the void space filled by He (He "bag")

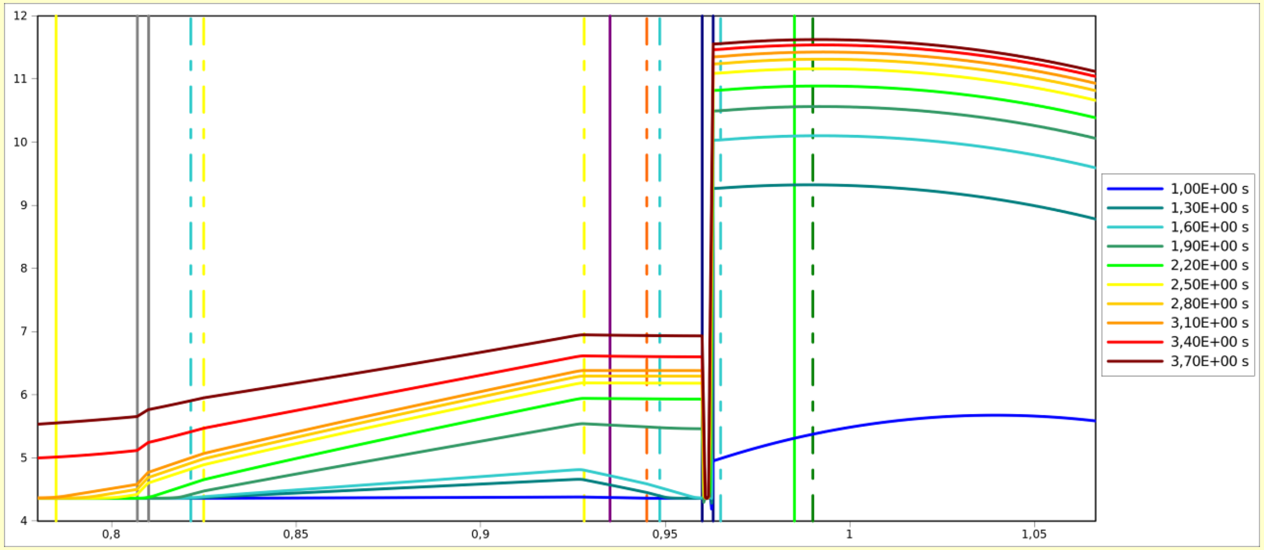


Backup slide

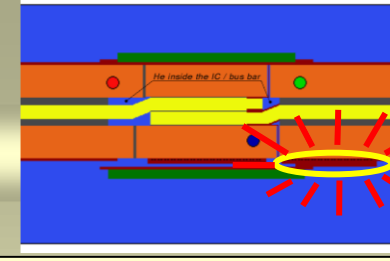


- Bus bar:

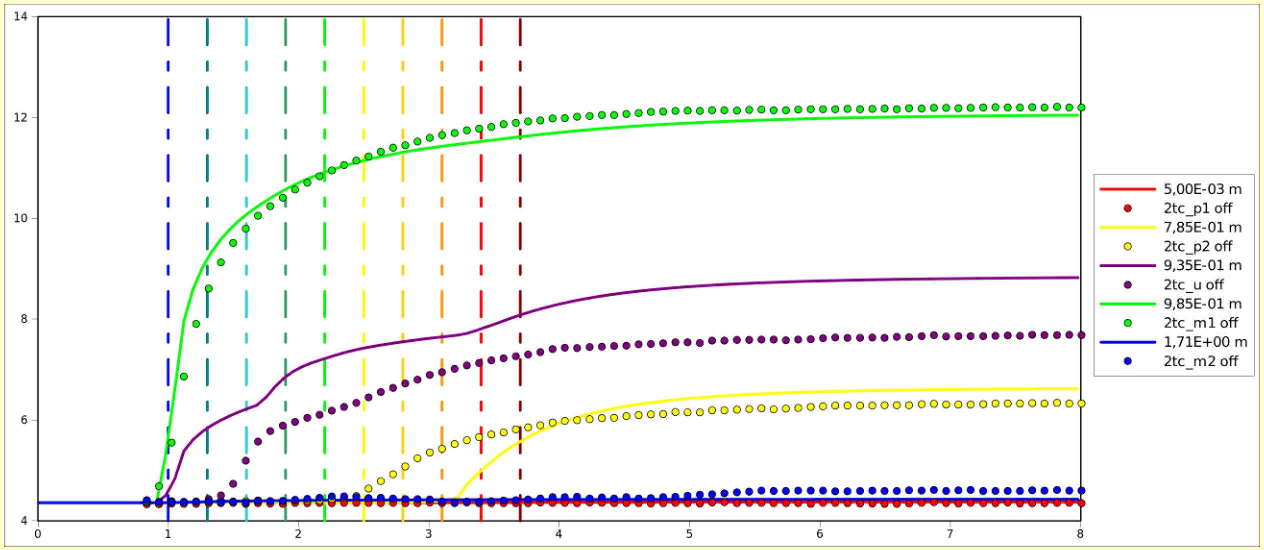


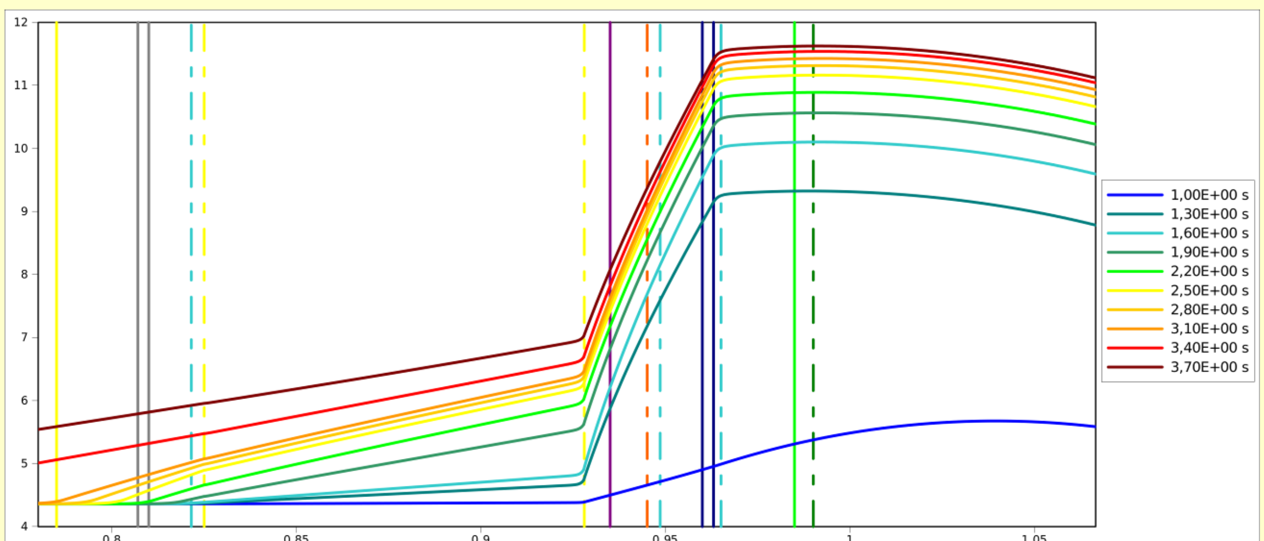


Backup slide



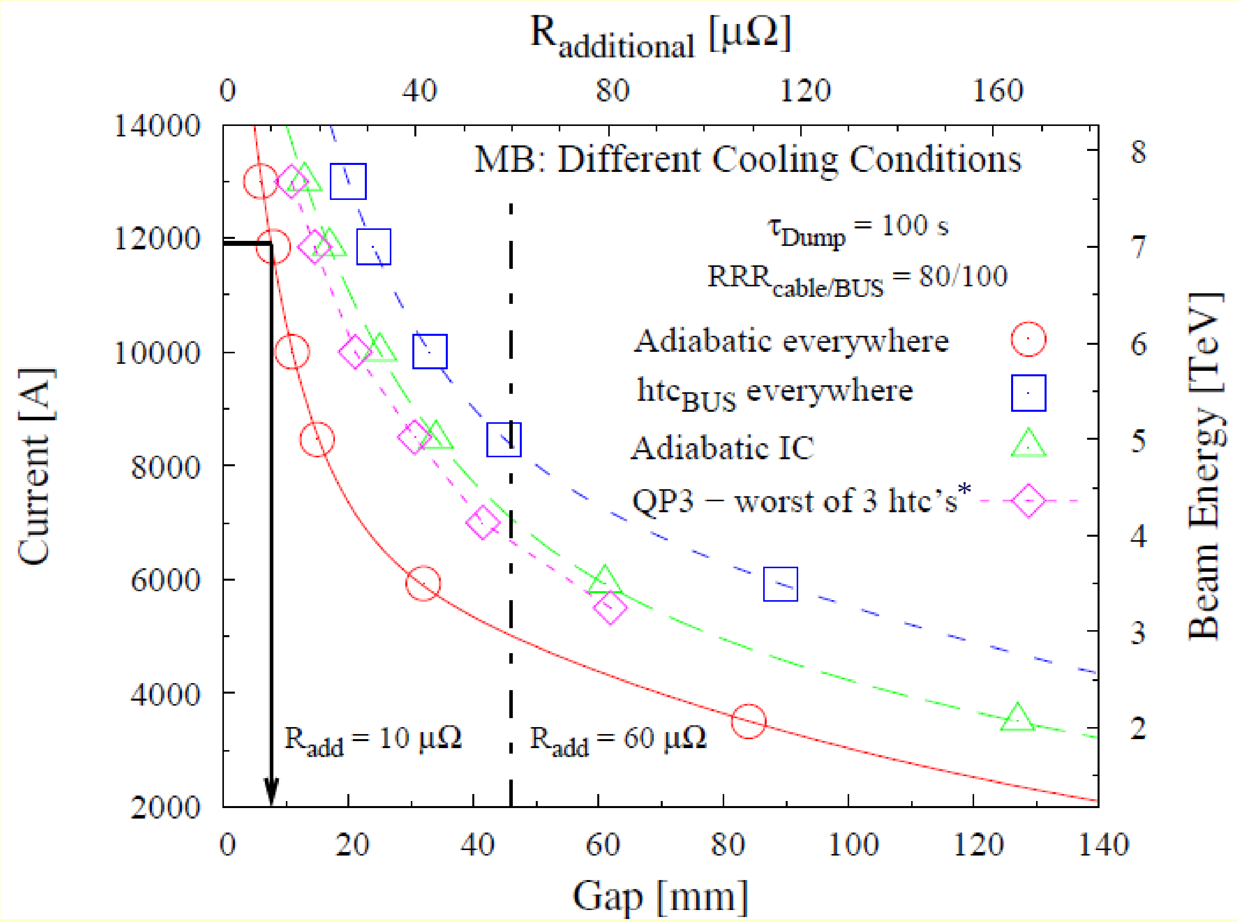
- SC cable:





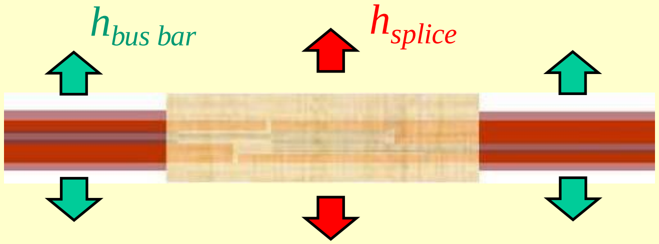
Stability dependence on IC HT mechanisms (1/2)

- Stability dependence on the IC Heat Transfer behavior :



Conservative hypothesis on:

- *Cable and bus bar RRR*
- *no He inside the IC*
- *no He-II contribution in the IC*



** Data courtesy of A. Verweij, TE-MPE (Chamonix 2010 LHC Performance Workshop)*