UNIVERSITY OF TWENTE.

KIT Karlsruhe Institute of Technology

CERN

AC Loss and inter-strand resistance in Impregnated *ReBCO* Roebel cables

P. Gao, M. Dhalle, H. Norder, B. van Nugteren, K. Yagotintsev, S. Wessel, A. Nijhuis
University of Twente, Faculty of Science & Technology, 7522 NB Enschede, The Netherlands

A. Kario, S. Otten, W. Goldacker
KIT, ITEP, Karlsruhe , Germany

L. Bottura, J. van Nugteren, G. Kirby, S. Tavares, S. Clement, L. Rossi and H. H.J. ten Kate
CERN, Geneva, Switzerland

EUCAS 2017
13th European Conference on Applied Superconductivity

EuCARD²
EuCARD-2 is co-funded by the partners and the European Commission under Capacities 7th Framework Programme, Grant Agreement 312453

3LO3-08: Geneva, 17 - 21 September, 2017

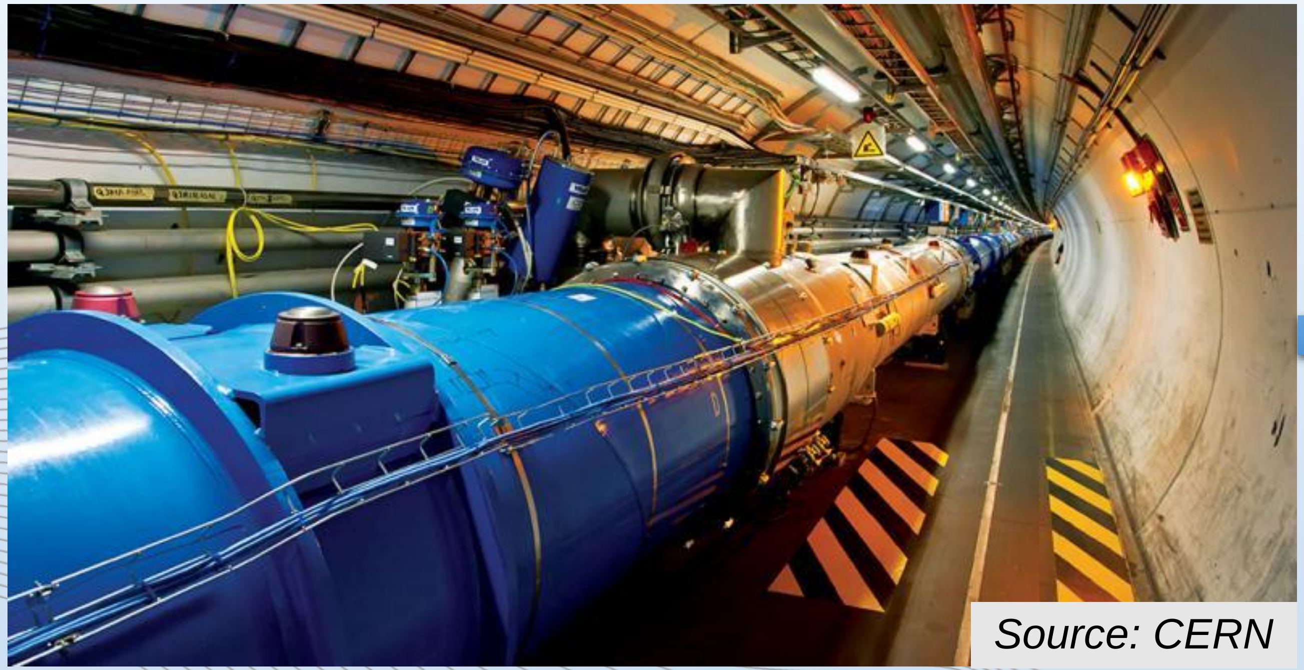
Outline of this presentation:

UNIVERSITY OF TWENTE.

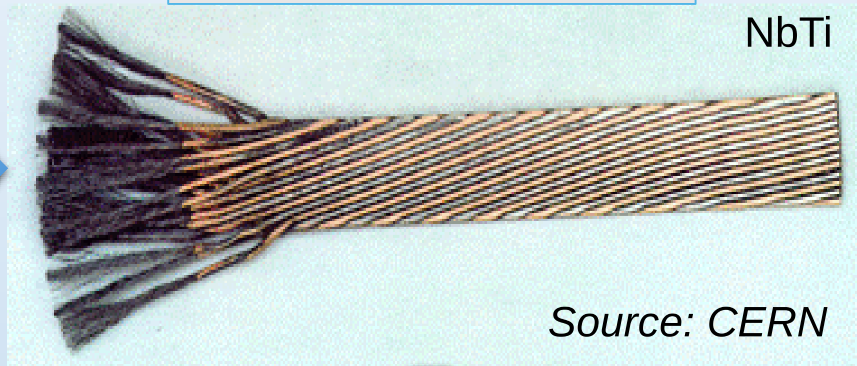
1. **Motivation**
2. Introduction
3. Inter-strand resistance of impregnated Roebel cable
4. AC losses of impregnated Roebel cable
5. Conclusions

EMS

1. Motivation


Source: CERN

LHC 8.3T



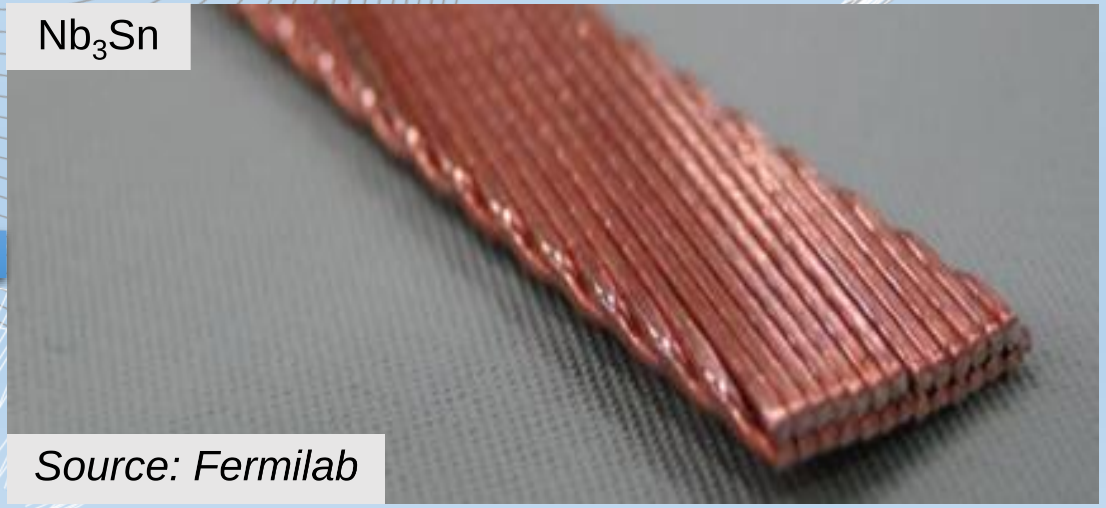
Source: CERN

EuCARD-2 ≥ 20T

HL-LHC 11T

FCC-EuroCirCol 16T

Source: KIT

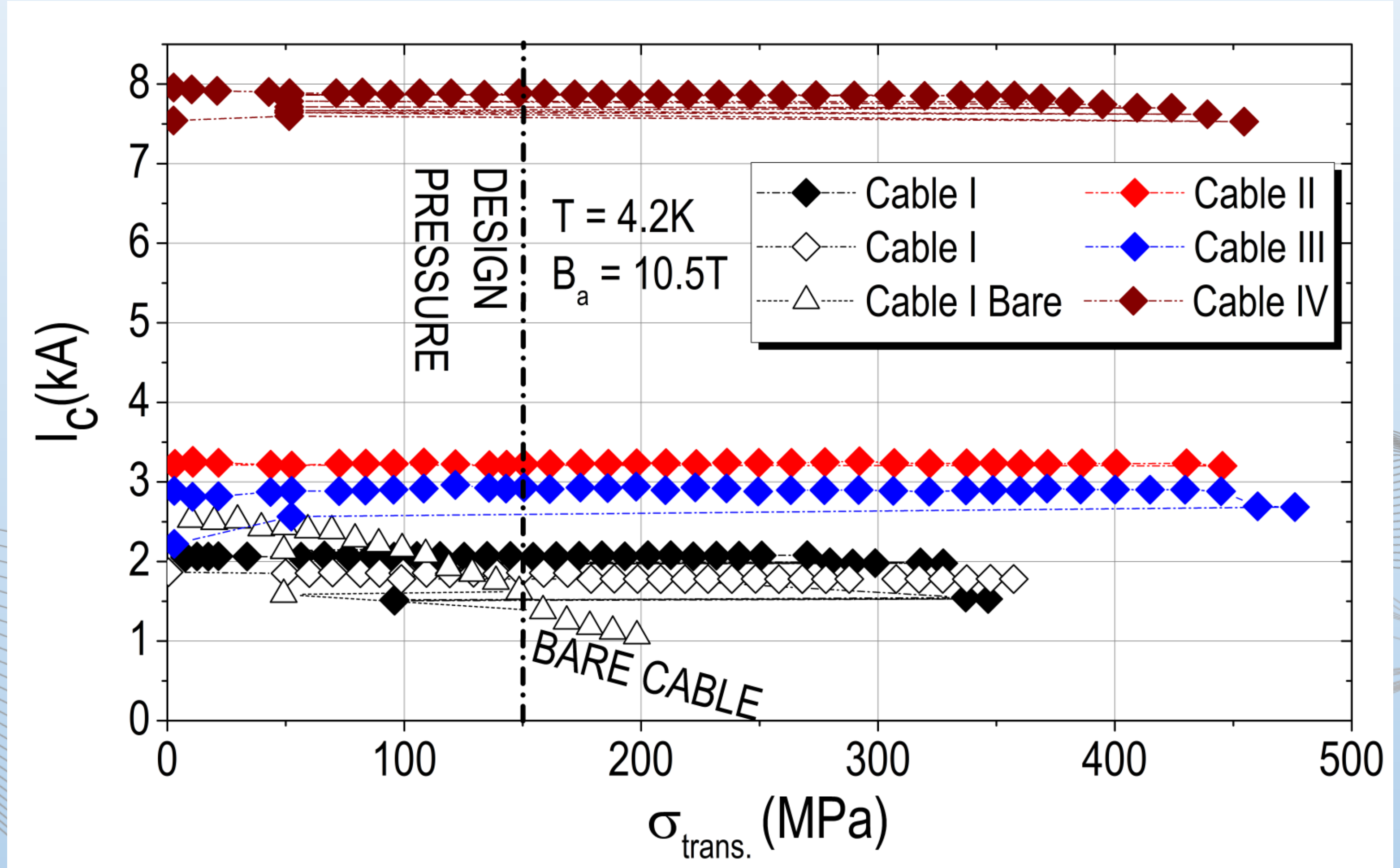


Source: Fermilab

1. Motivation

Transverse pressure tolerance?

EuCARD-2 ≥ 20T



Impregnation ⇒ σ_{trans} > 400MPa !

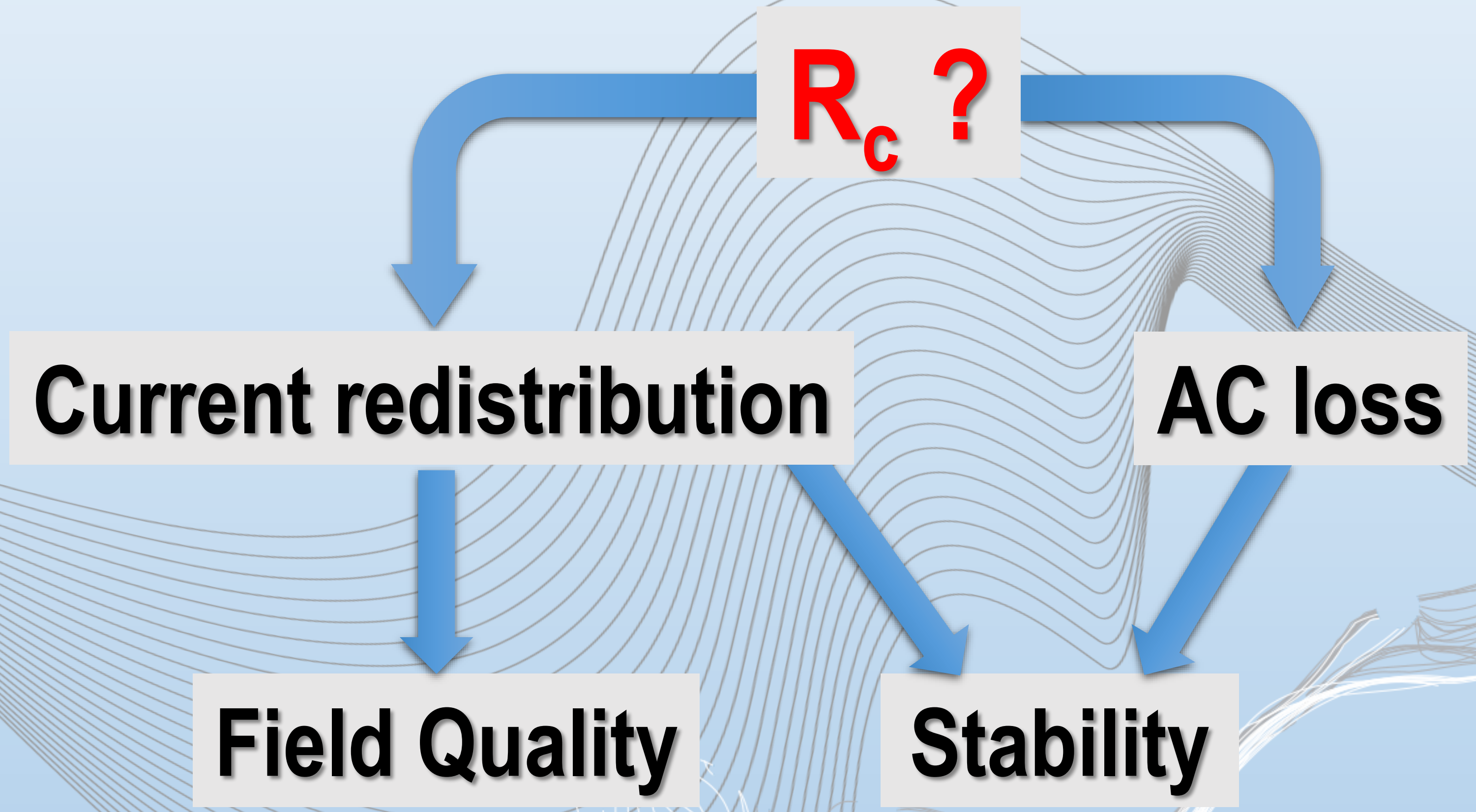
Source: ***P. Gao, M. Dhallé et.al.*** *"The effect of tape layout and impregnation method on transverse pressure dependence of critical current in REBCO Roebel cables", to be published*

UNIVERSITY OF TWENTE. EMS

1. Motivation

Inter-strand resistance?

EuCARD-2 ≥ 20T

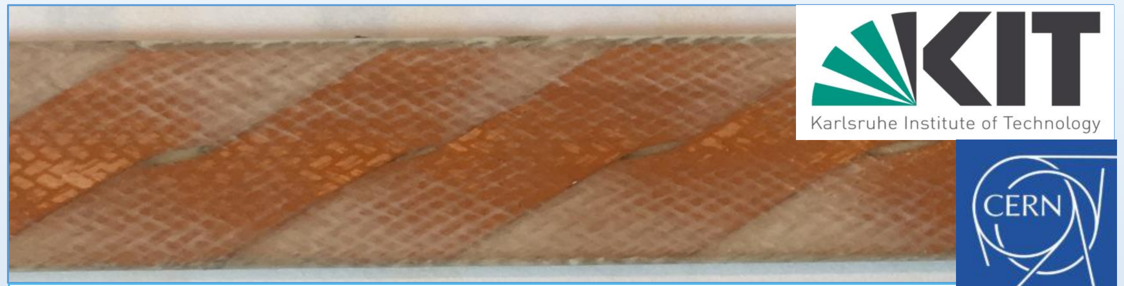


Outline

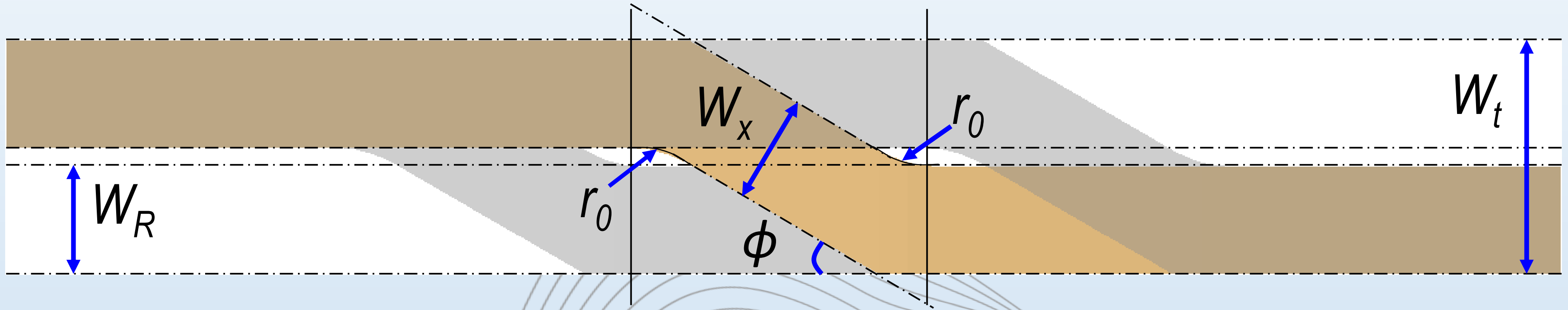
UNIVERSITY OF TWENTE.

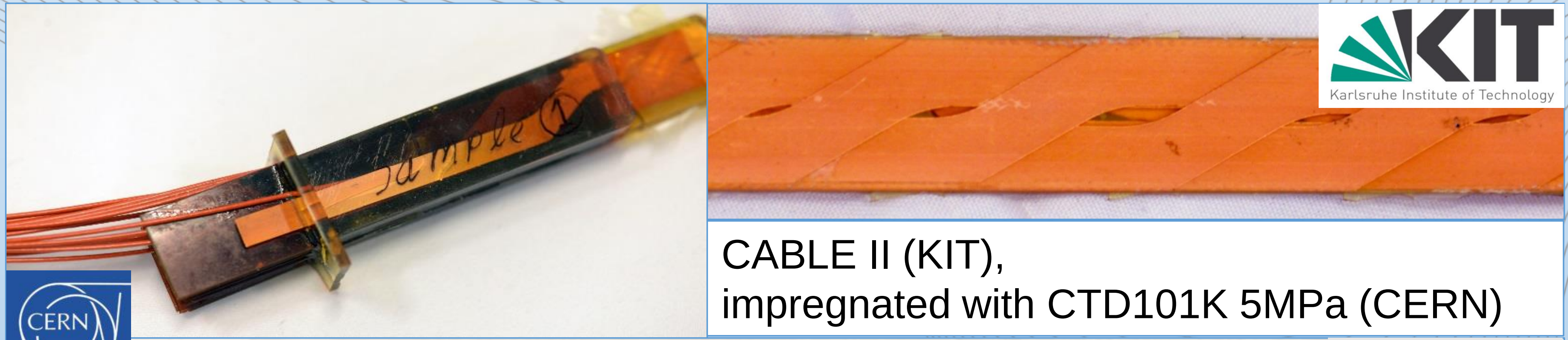
EMS

2. Introduction : samples



CABLE I(KIT),
impregnated with CTD101G, filled with alumina powder, 5MPa (CERN)





CABLE II (KIT),
impregnated with CTD101K 5MPa (CERN)

Symbol	Value	Description
N_S	15	Number of strands
d_s	0.1 mm	Strand thickness
d_c	0.8 mm	Cable total thickness
d_i	0.1 mm	Insulation thickness
W_r	5.5 mm	Strand width
W_t	12.0 mm	Cable width
W_x	5.5 mm	Cross over width
W_c	1.0 mm	Channel width
Φ	30°	Cross over angle
L_{tp}	226 mm	Transposition pitch
r_i	6.0 mm	Inner radius
r_o	6.0 mm	Outer radius

Outline of this presentation:

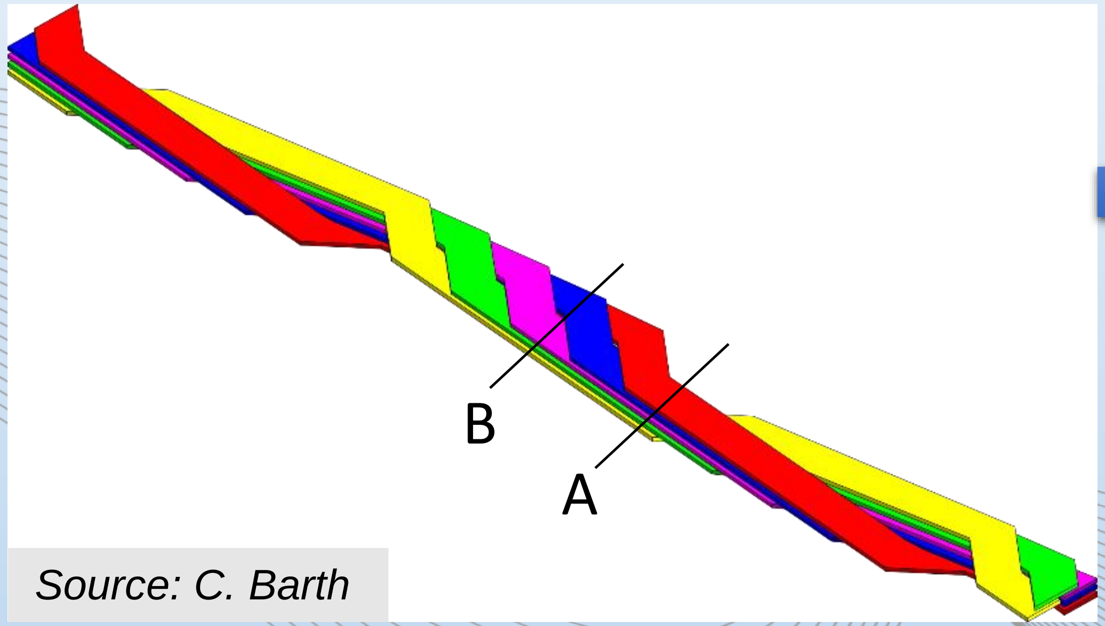
UNIVERSITY OF TWENTE.

1. Motivation
2. Introduction
3. **Inter-strand resistance of impregnated Roebel cable**
4. AC losses of impregnated Roebel cable
5. Conclusions

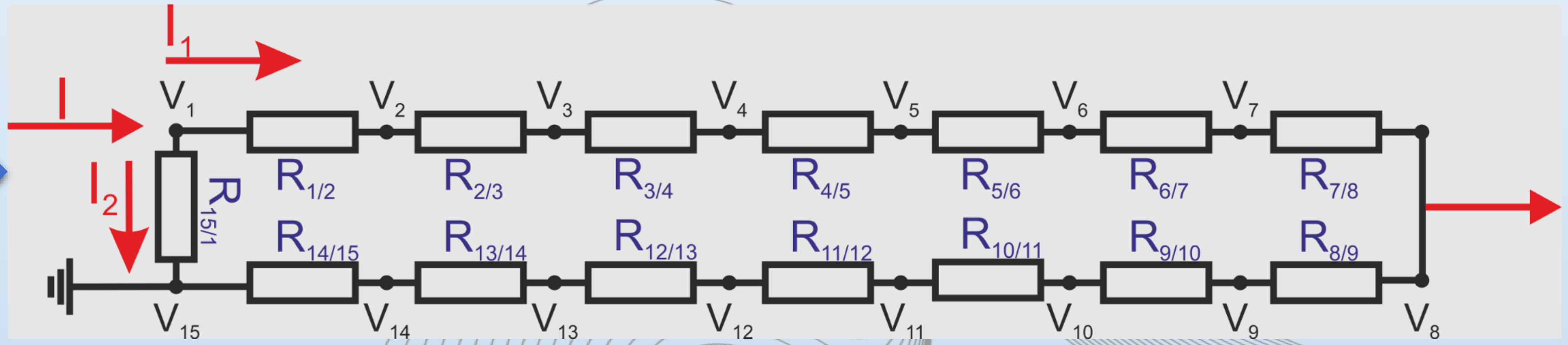
EMS

3. R_c of impregnated Roebel cable

Schematic of strands layout

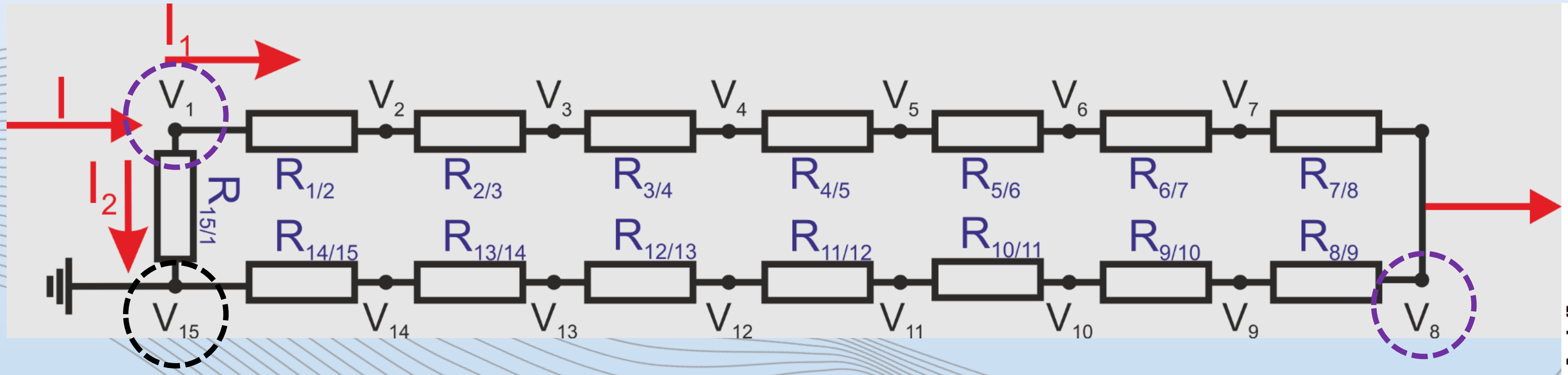


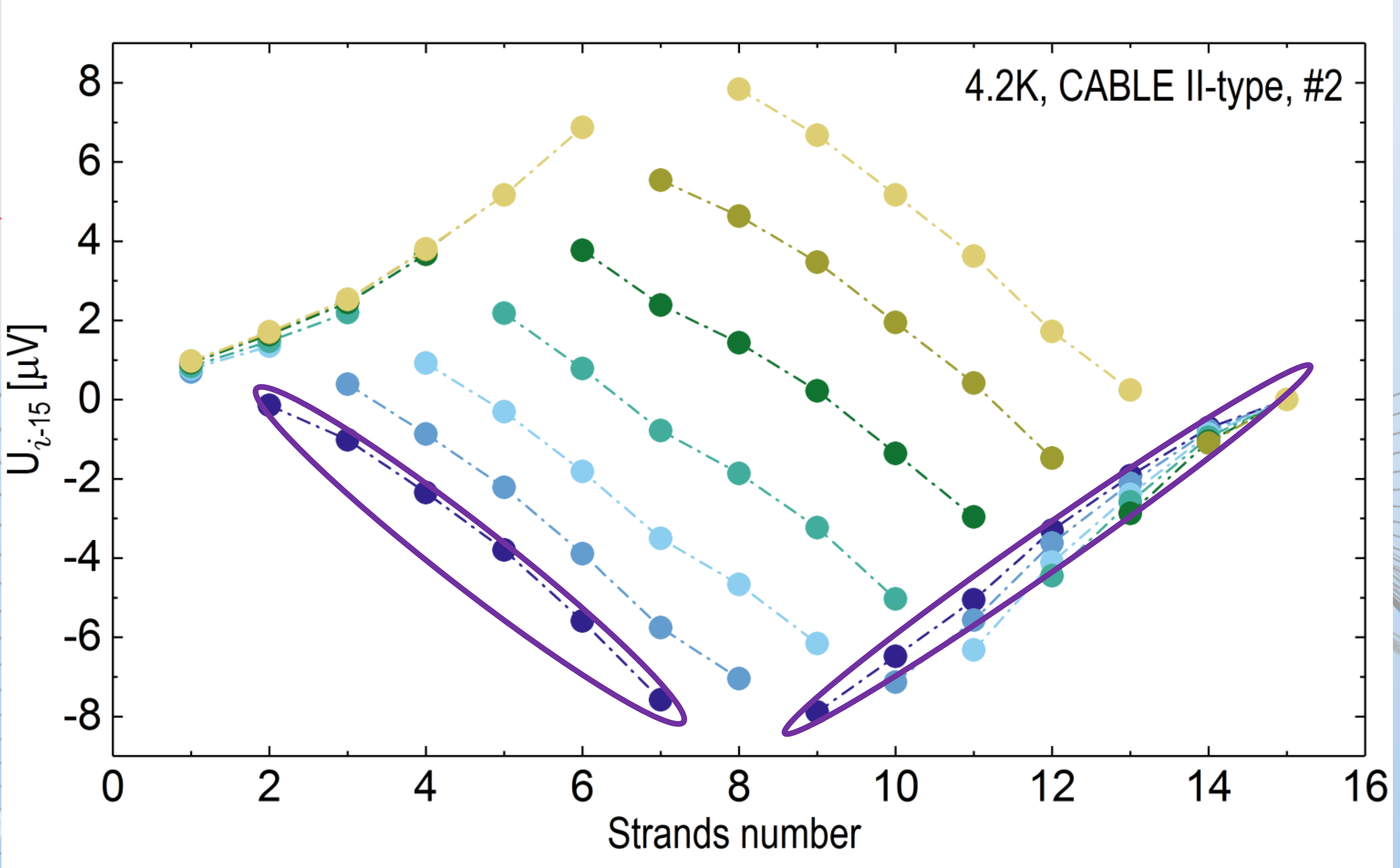
Circuit diagram (15str.)



- **2 neighbors per stand**
- **15 soldered contact taps**
- **V_1 ~ V_{15}: equipotential (S.C. layer)**
- **$R_{i/j}$: contact resistance between neighboring stands i & j**

3. R_c of impregnated Roebel cable



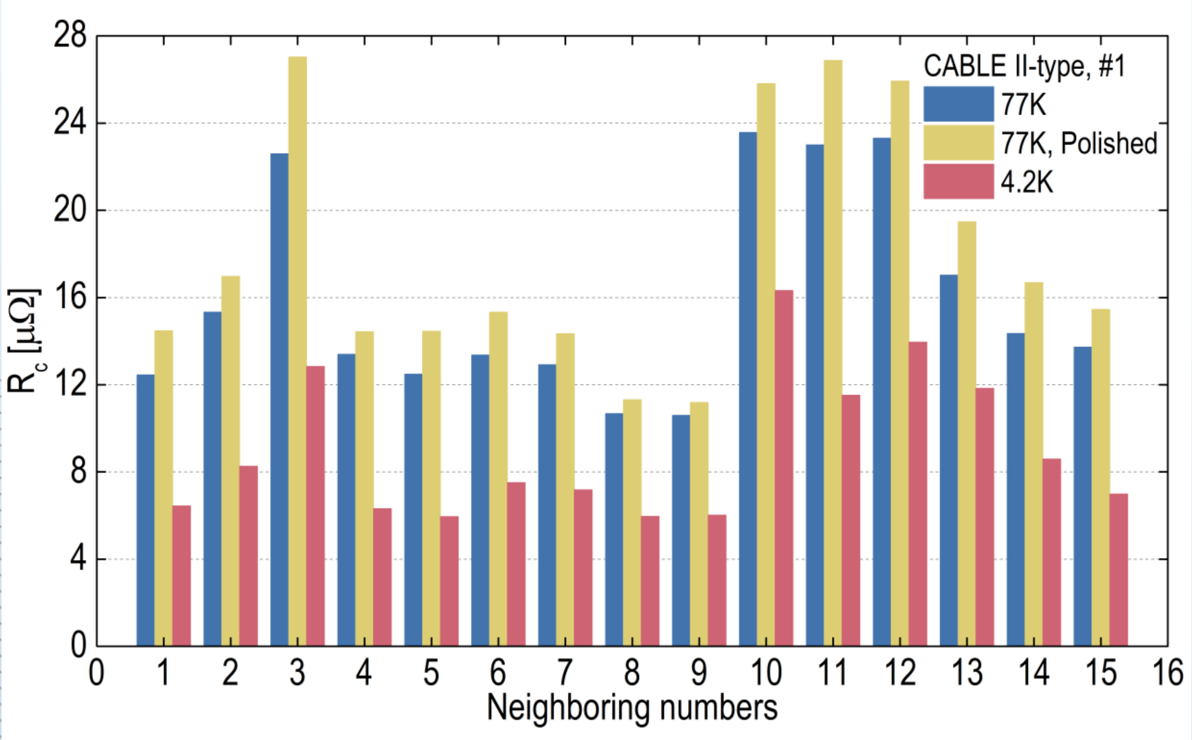


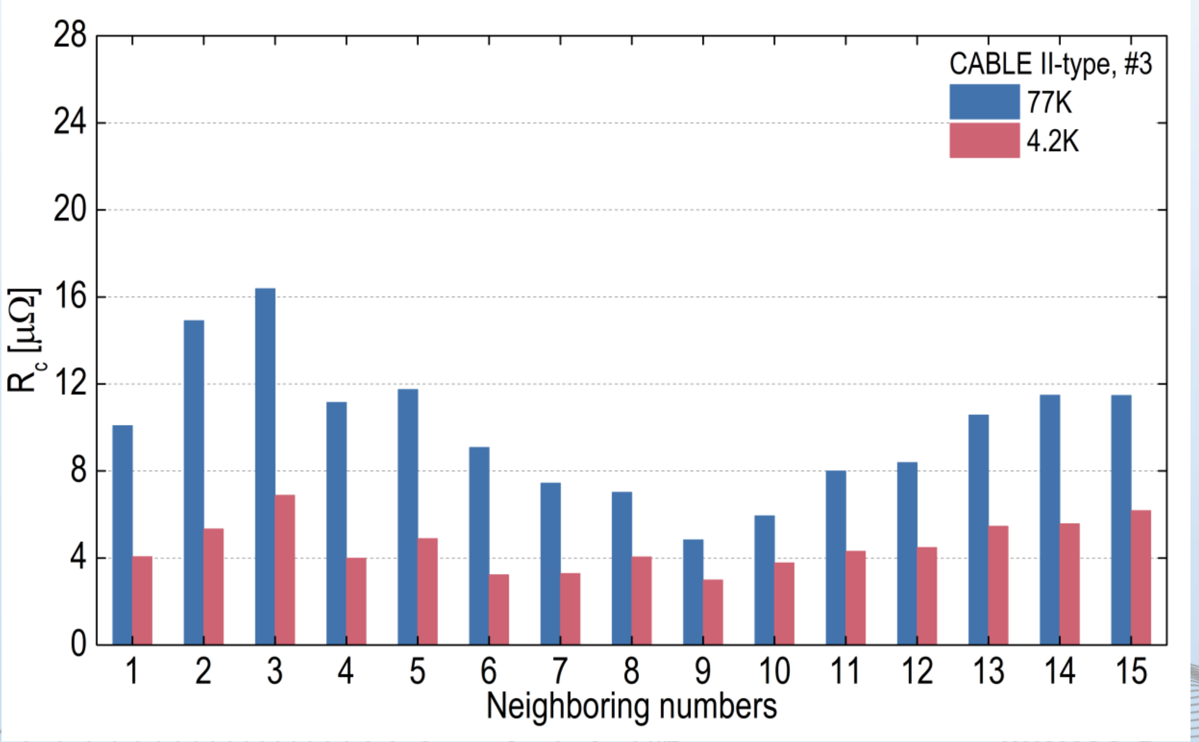
Method:

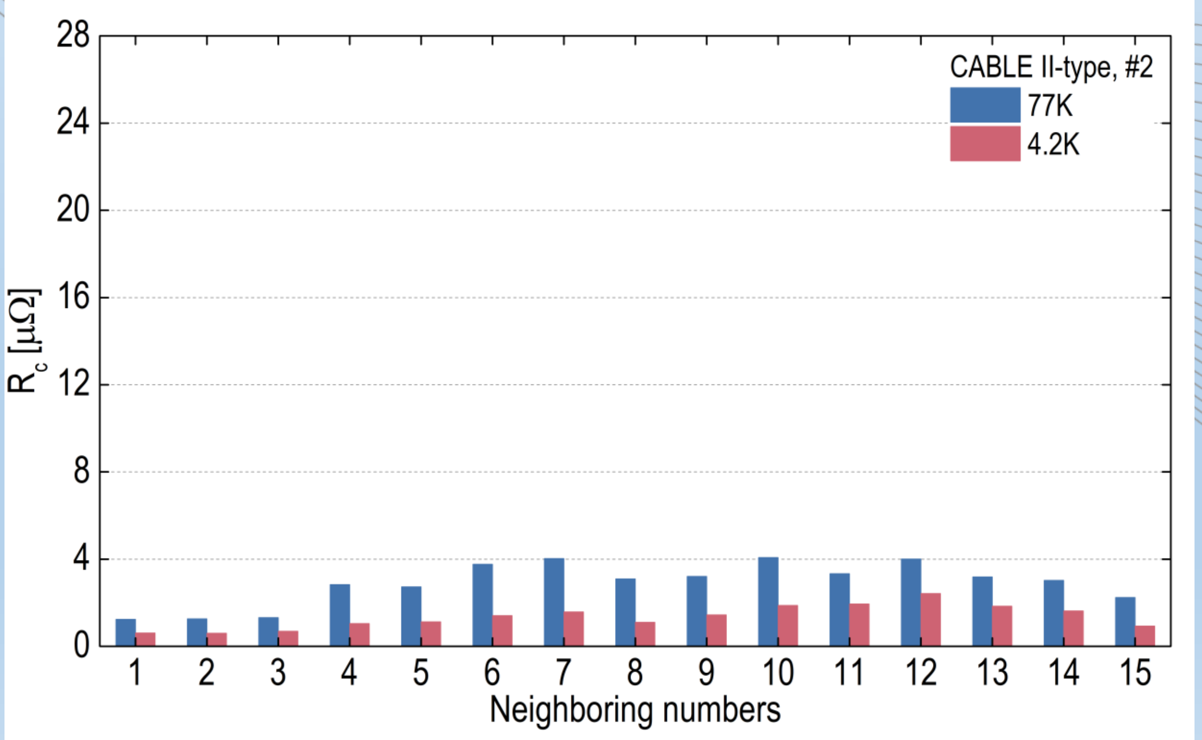
- 2 taps as current lead (e.g. 1 and 8)
- V_{15} is grounded, as a ref. volt. potential
- $U_{i/15}$ are measured (e.g. purple data)
- cycle current lead position

$R_{i/j}$ can then be calculated by solving system of equations

3. R_c of impregnated Roebel cables



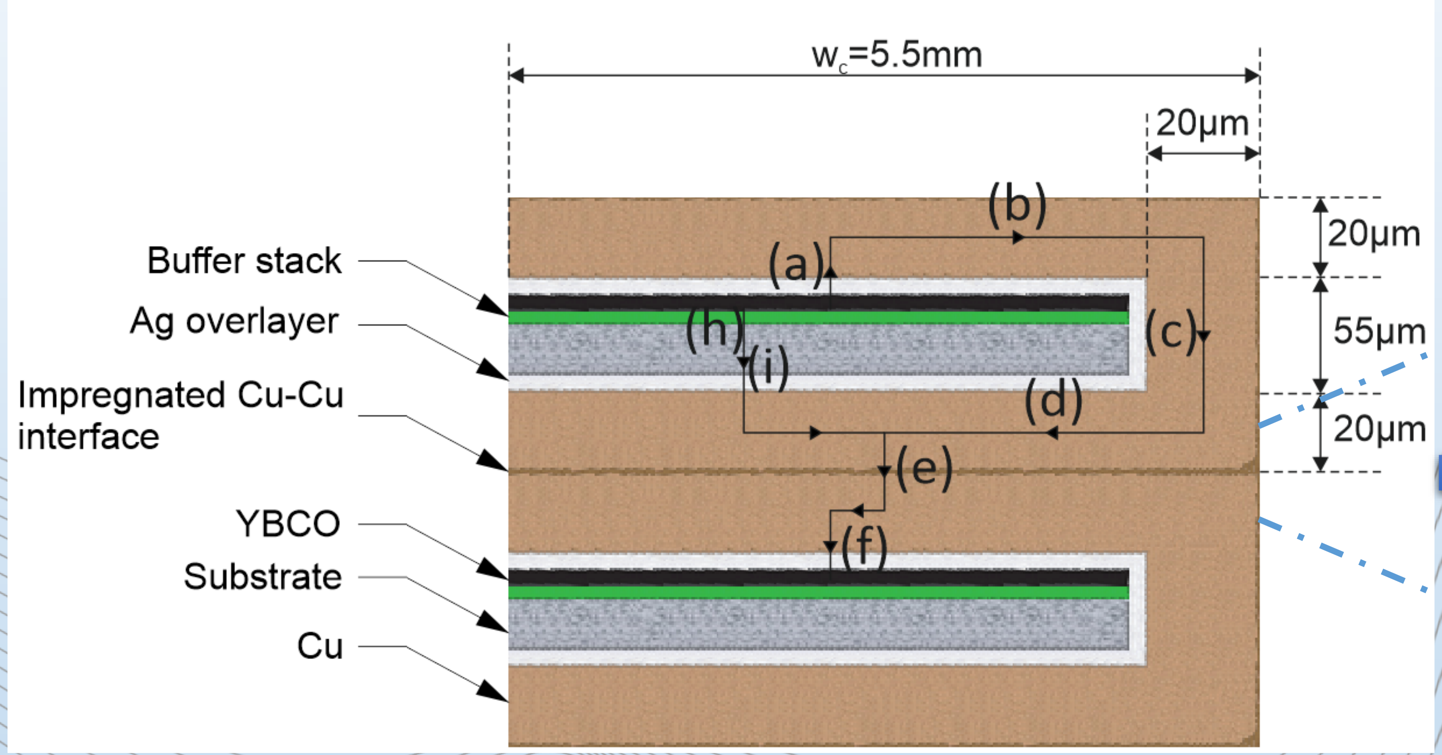


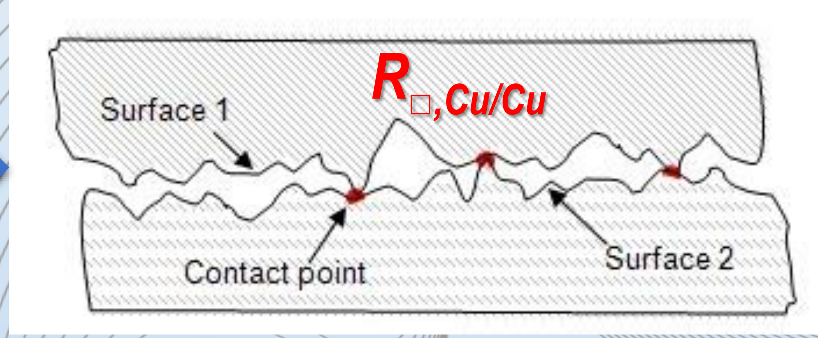


Avg. R_c between neighbors

T	# 1 $R_c(\mu\Omega)$	# 2 $R_c(\mu\Omega)$	# 3 $R_c(\mu\Omega)$
77K	15.9	2.9	9.9
77K polished	18.0	-	-
4.2K	**9.1**	**1.4**	**4.6**
$R_c(77K)/R_c(4.2K)$	1.8 ~ 2.0	2.1	2.2

3. R_c of impregnated Roebel cable





$$R = \frac{\rho l}{A}$$

$$R = \frac{R_{\square}}{A}$$

Current path: ReBCO ⟶ Ag ⟶ Cu(b) ⟶ Cu(c) ⟶ Cu(d) ⟶ Cu-Cu(e) ⟶ Cu(f) ⟶ Ag ⟶ ReBCO

T	$R_{c,\ S.C./Ag}\ (\mu\Omega)$	$R_{c,S.C./Ag/Cu(b)}(\mu\Omega)$	$R_{c,Cu(c)}(\mu\Omega)$	$R_{c,Cu(d)+Cu\text{-}Cu(e)}(\mu\Omega)$	$R_{c,Cu(c)}(\mu\Omega)$	$R_{c,Cu(c)/Ag/S.C.}\ (\mu\Omega)$
77K	0.31~0.44	0.11~0.15	8.5E-2		6.5E-5	2.3E-3~4.7E-3
4.2K	1.6E-3~1.6E-2	4.4E-3~4.4E-2	3.6E-2		2.8E-5	9.3E-5~9.3E-4

*Ref.: **C. Zhou**, "Intra wire resistance and strain affecting the transport properties of Nb_3Sn strands in Cable-in-Conduit Conductors", PhD dissertation, University of Twente, 2014*

***T. Holúbek, M. Dhallé and P. Kováč**, "Current transfer in MgB_2 wires with different sheath materials", University of Twente, SUST, 20, 2007*

Assuming

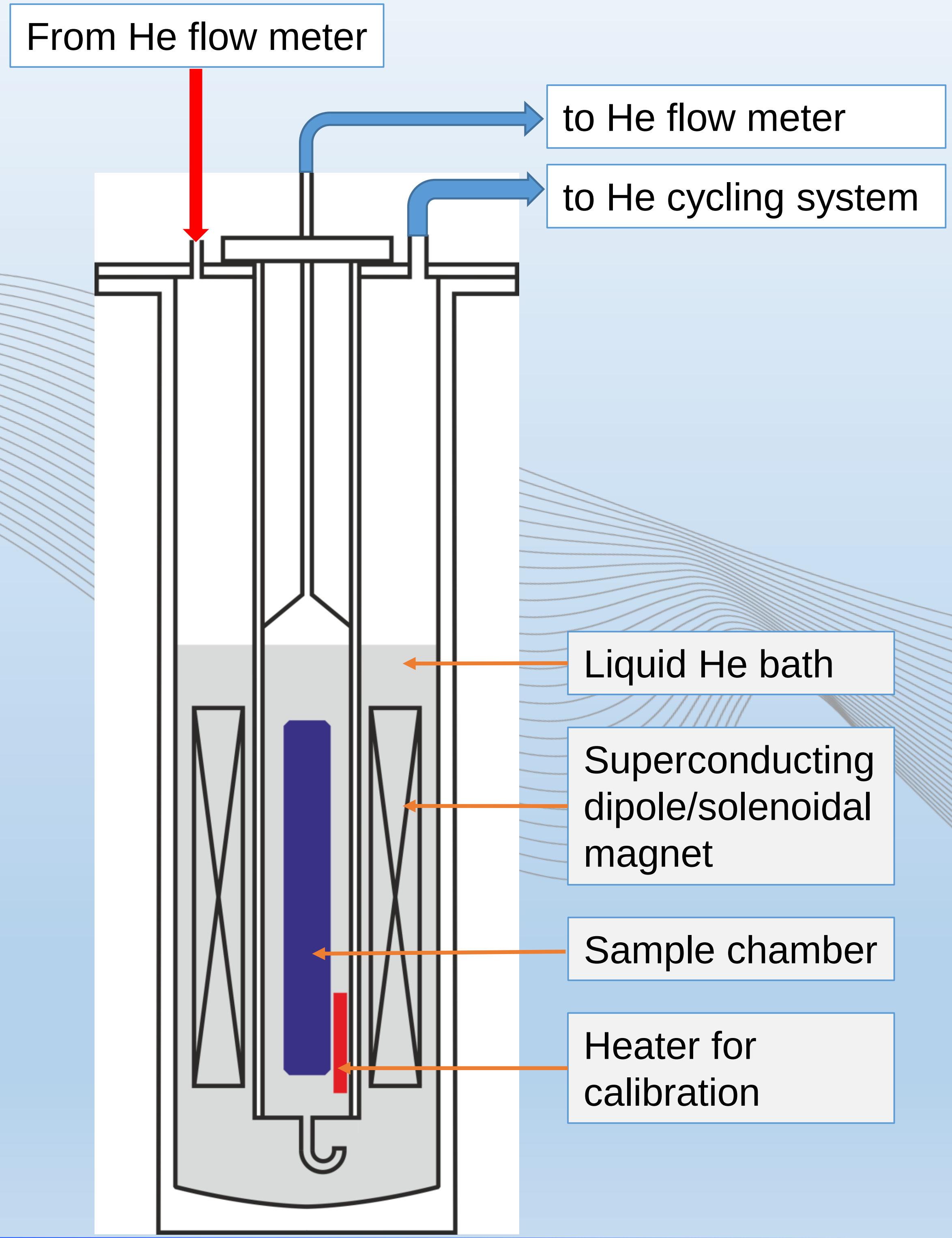
$R_{\square,Cu/Cu}$ (77K) ~ 10 to 20 nΩ·m²
$R_{\square,Cu/Cu}$ (4.2K) ~ 0.5 to 10 nΩ·m²

Outline of this presentation:

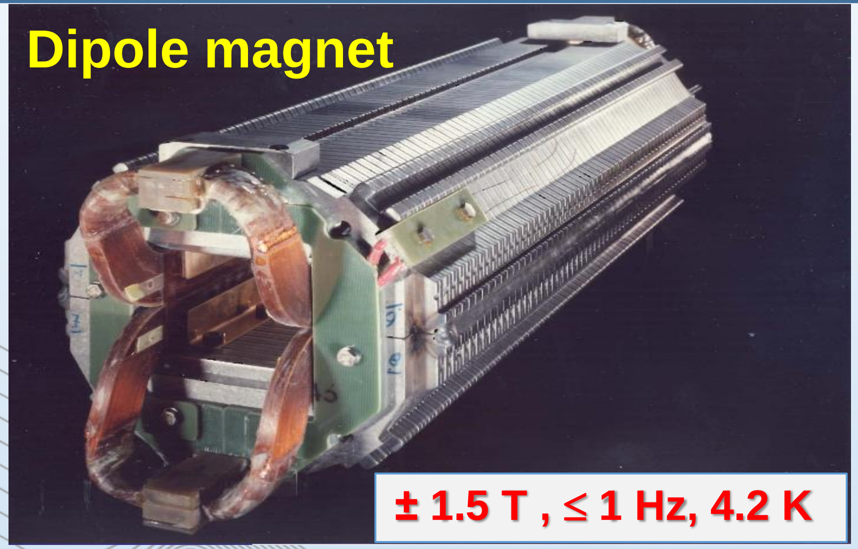
UNIVERSITY OF TWENTE.

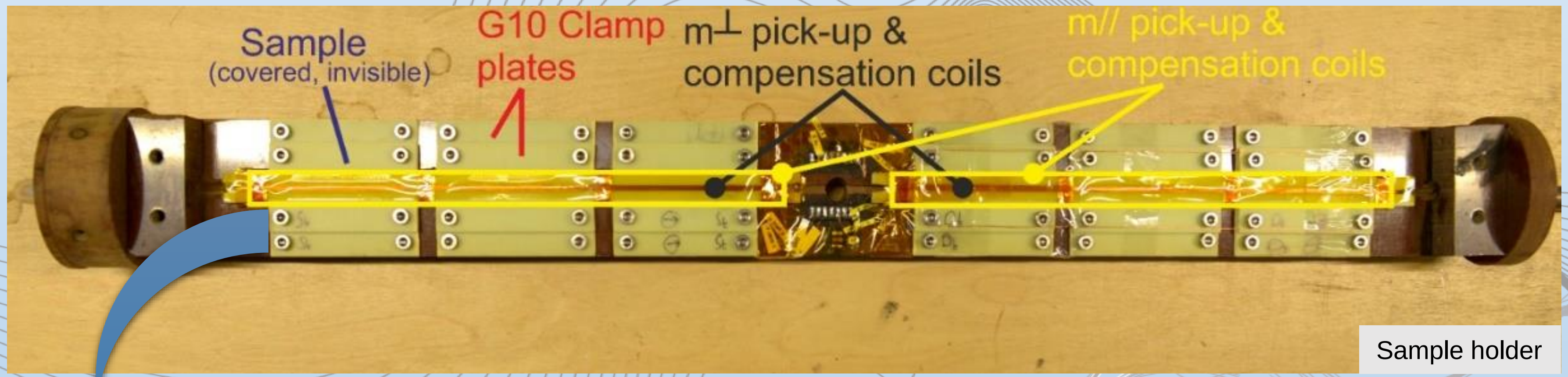
1. Motivation
2. Introduction
3. Inter-strand resistance of impregnated Roebel cable
4. **AC losses of impregnated Roebel cable**
5. Conclusions

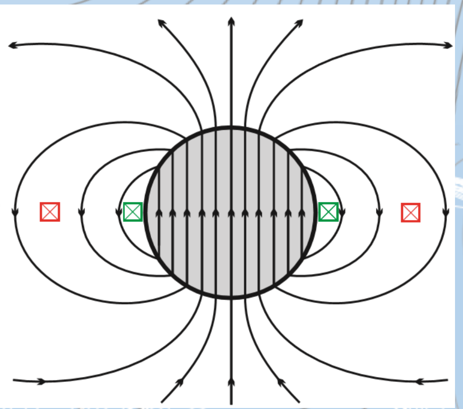
4. AC losses : Instrumentation



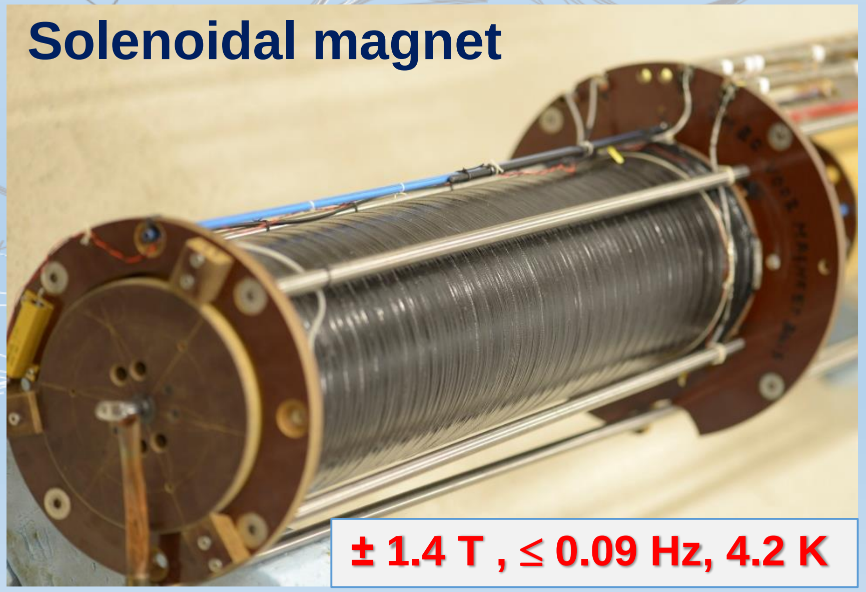
AC loss measured by gas flow calorimetry and magnetisation methods.





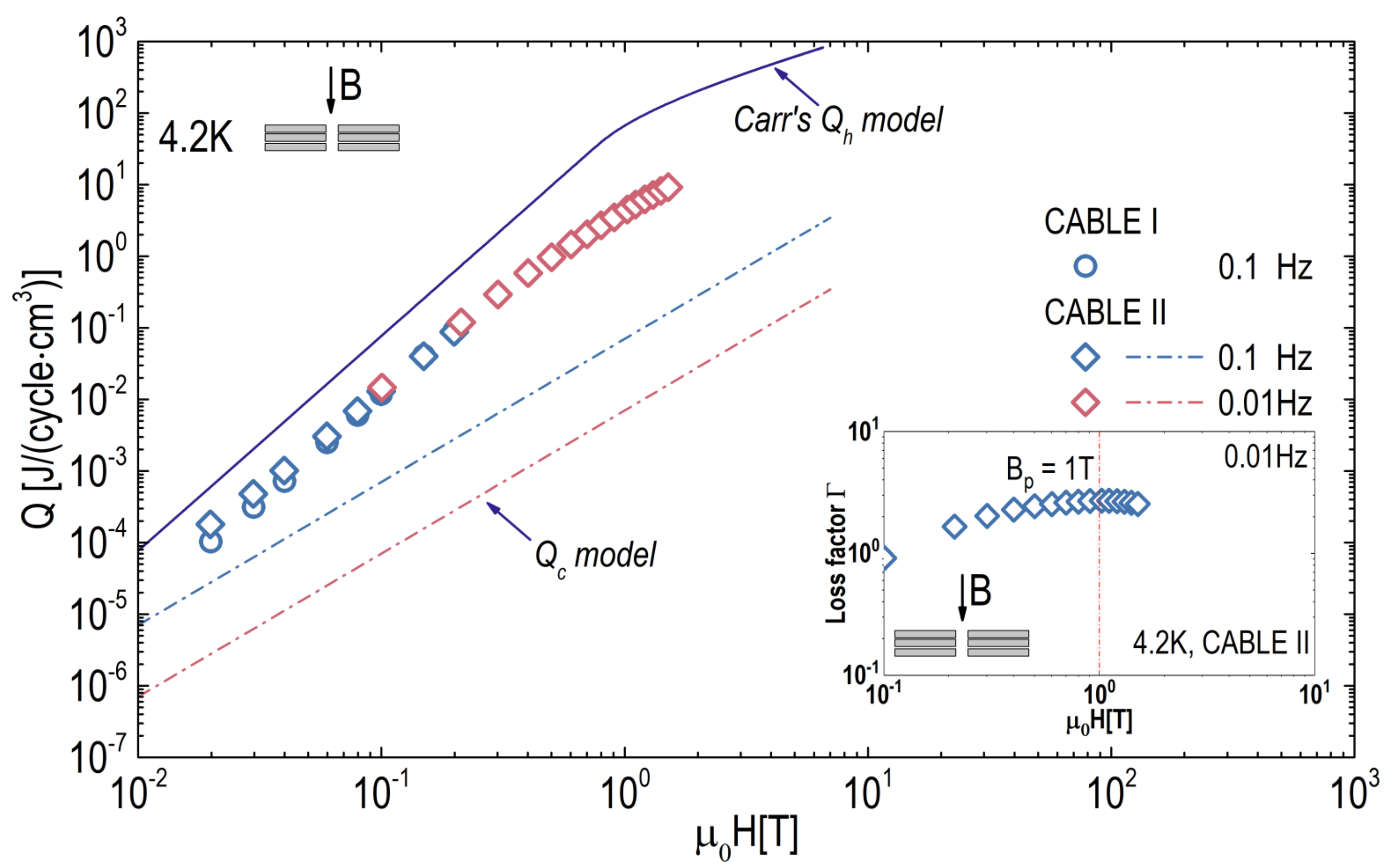


Filling factor effect

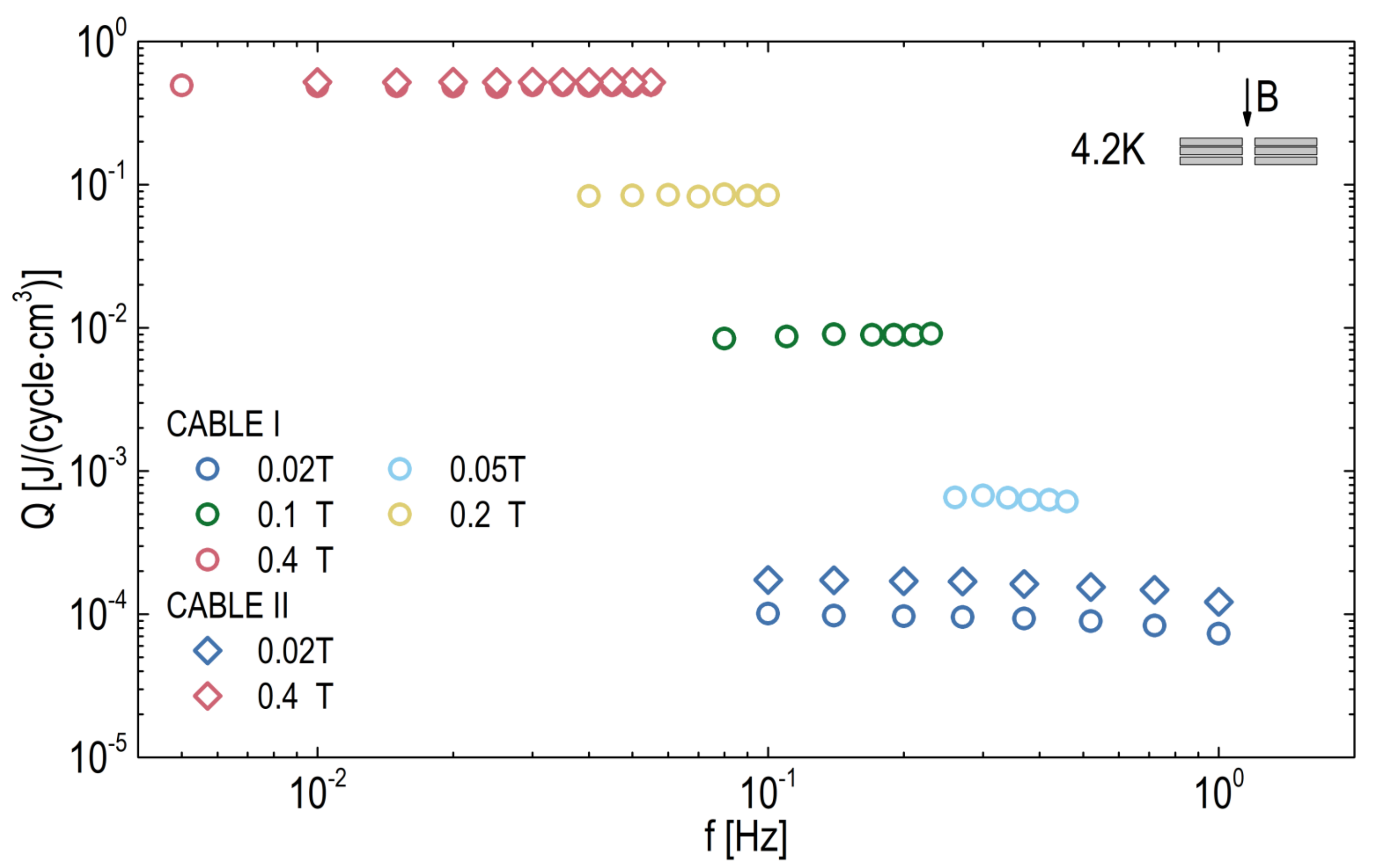


4. AC losses @ B⊥, 4.2K

Amplitude dependence



Frequency dependence



- AC losses are dominated by hysteresis
- No coupling losses are observed in exp. window

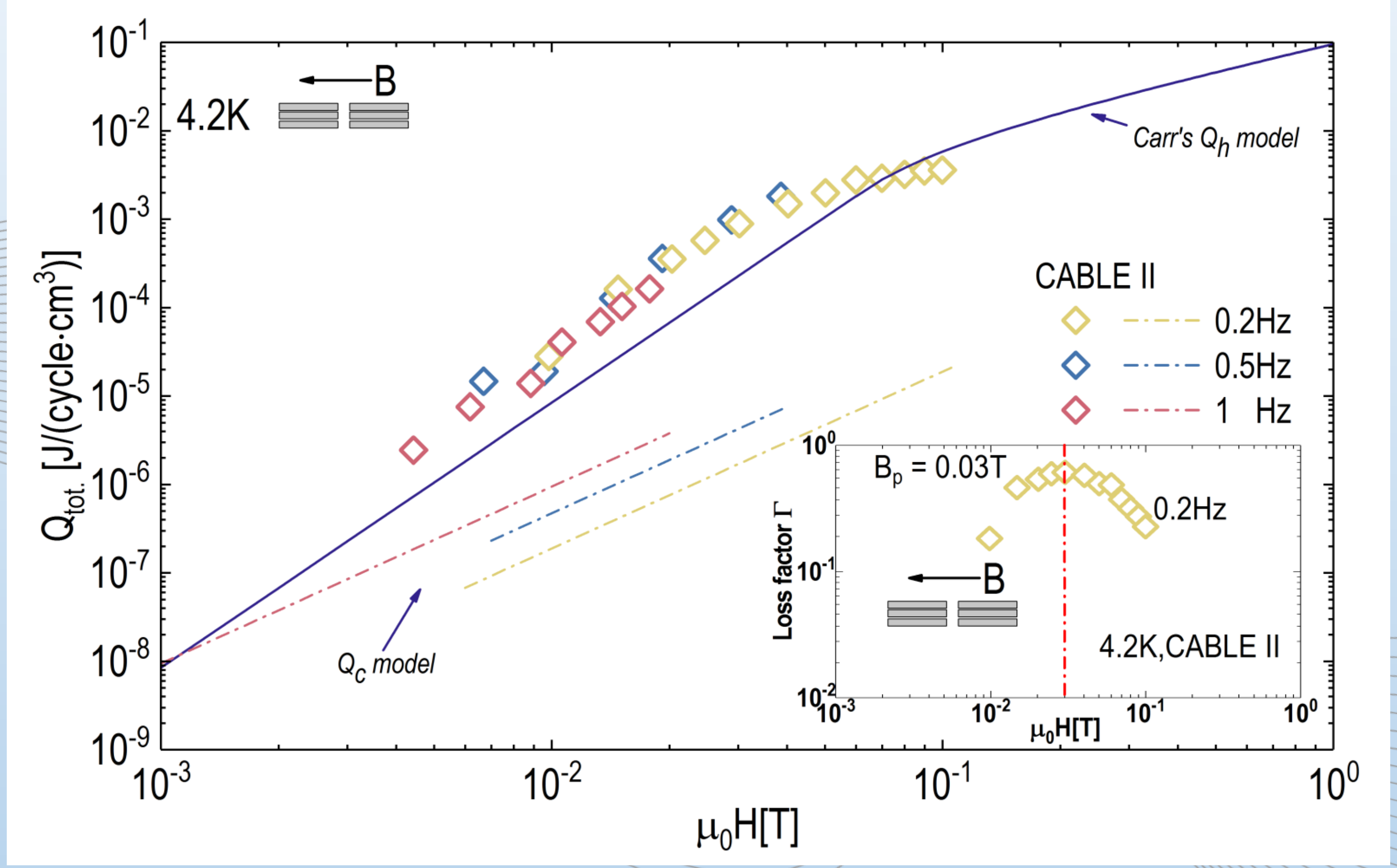
→ **Both in model prediction & experiment**

- Tested : $B_{p\perp} \approx$ 1T; Modelling: $B_{p\perp}$ = 0.769T

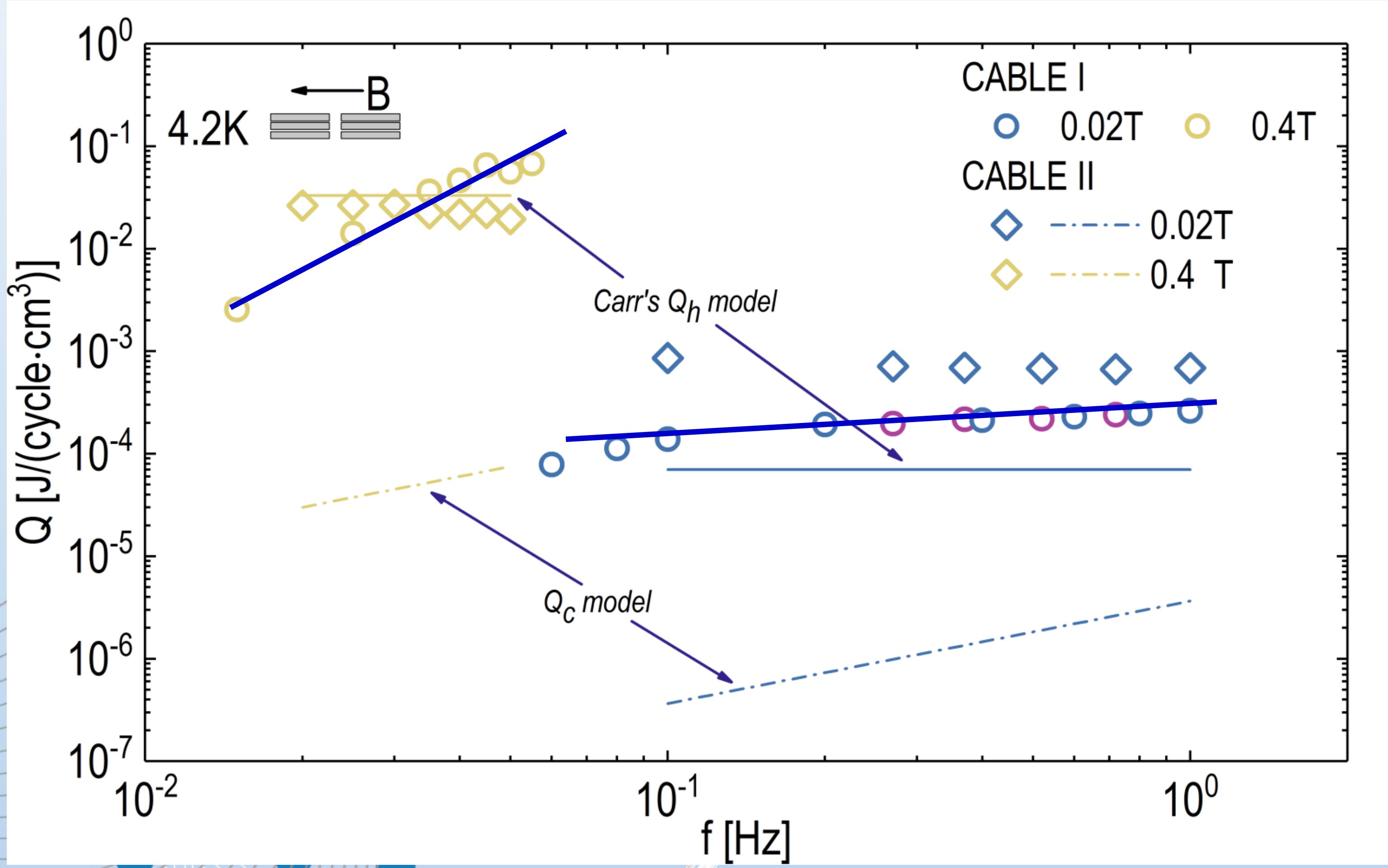
Carr's Q_h model, ref. : ***W. J. Carr. Jr.*** *"AC Loss and Macroscopic Theory of Superconductors", CRC Press, 5 Jul 2001, USA*

4. AC losses @ B//, 4.2K

Amplitude dependence



Frequency dependence

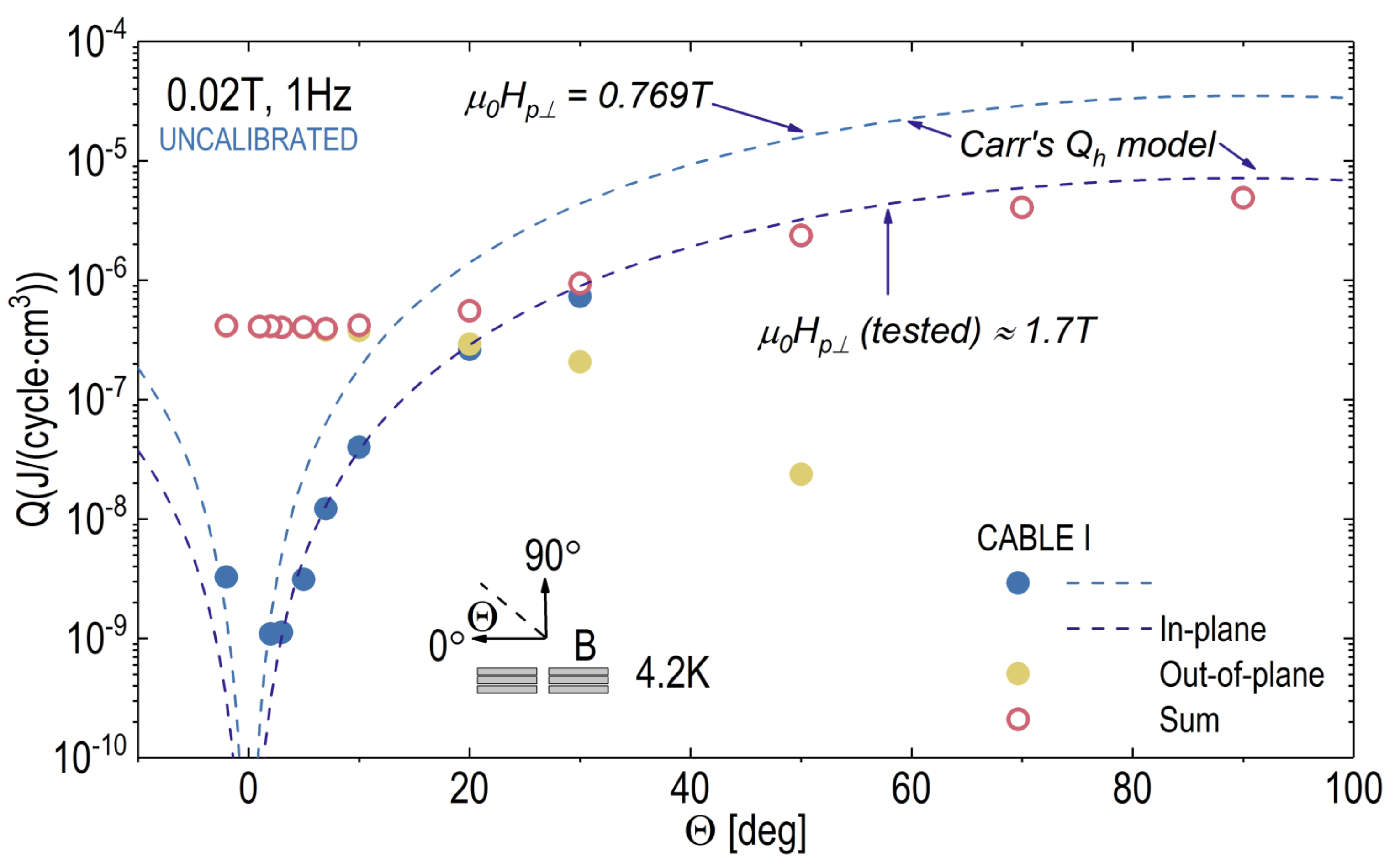


CABLE II

- AC losses are dominated by hysteresis
- No coupling losses are observed in exp. window
- Tested: $B_{p//} \approx 0.03T$; Modelling $B_{p//} = 0.06T$
- Q_c is much lower than measured Q_h in exp. window, which is identical with modelling estimation

3. AC losses @B_a=±0.02T(θ), f=1Hz, 4.2K

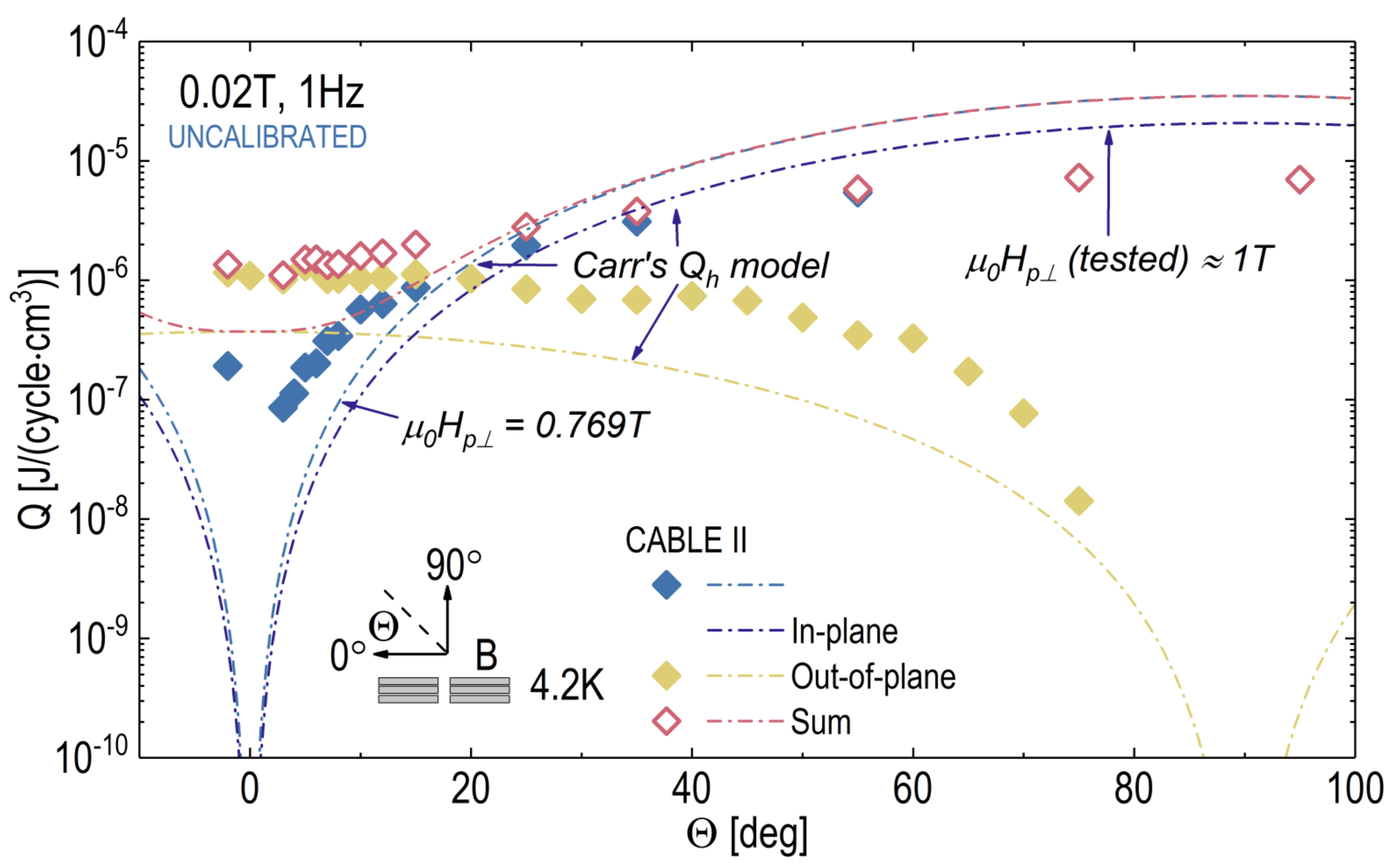
CABLE I: AC losses-B_a angle θ



- The predominant role of AC losses: from **Coupling** to **Hysteresis** with the **increase θ(0°~90°)**
- Q_h model fits well with data when use $\mu_0 H_{p\perp} \approx 1.7T$

Tested $\mu_0 H_{p\perp} \approx 1.7T$, ref. : ***J. Pelegrin, I. Falorio, E. A. Young, Y. Yang et.al.*** *University of Southampton.*

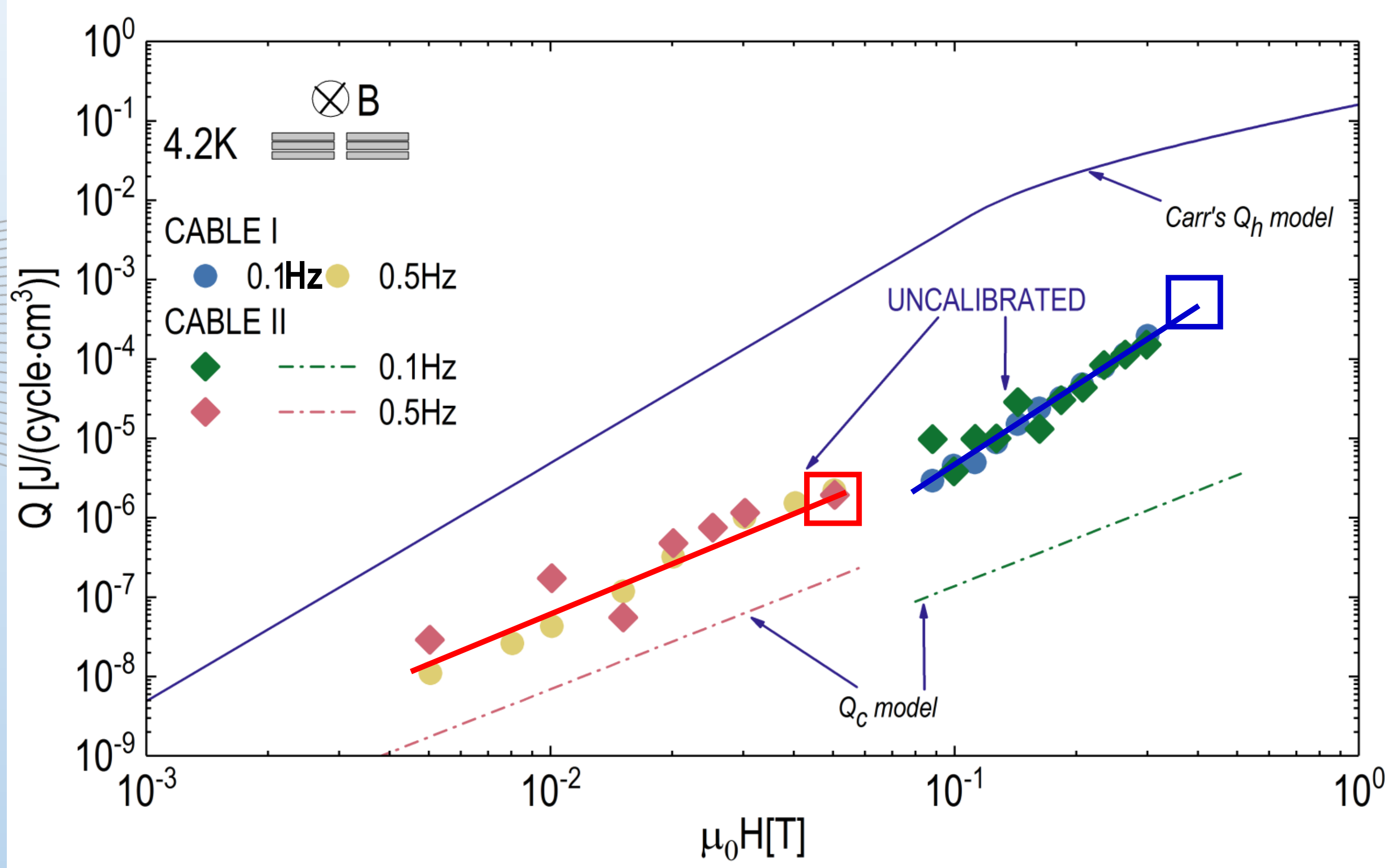
CABLE II: AC losses-B_a angle θ



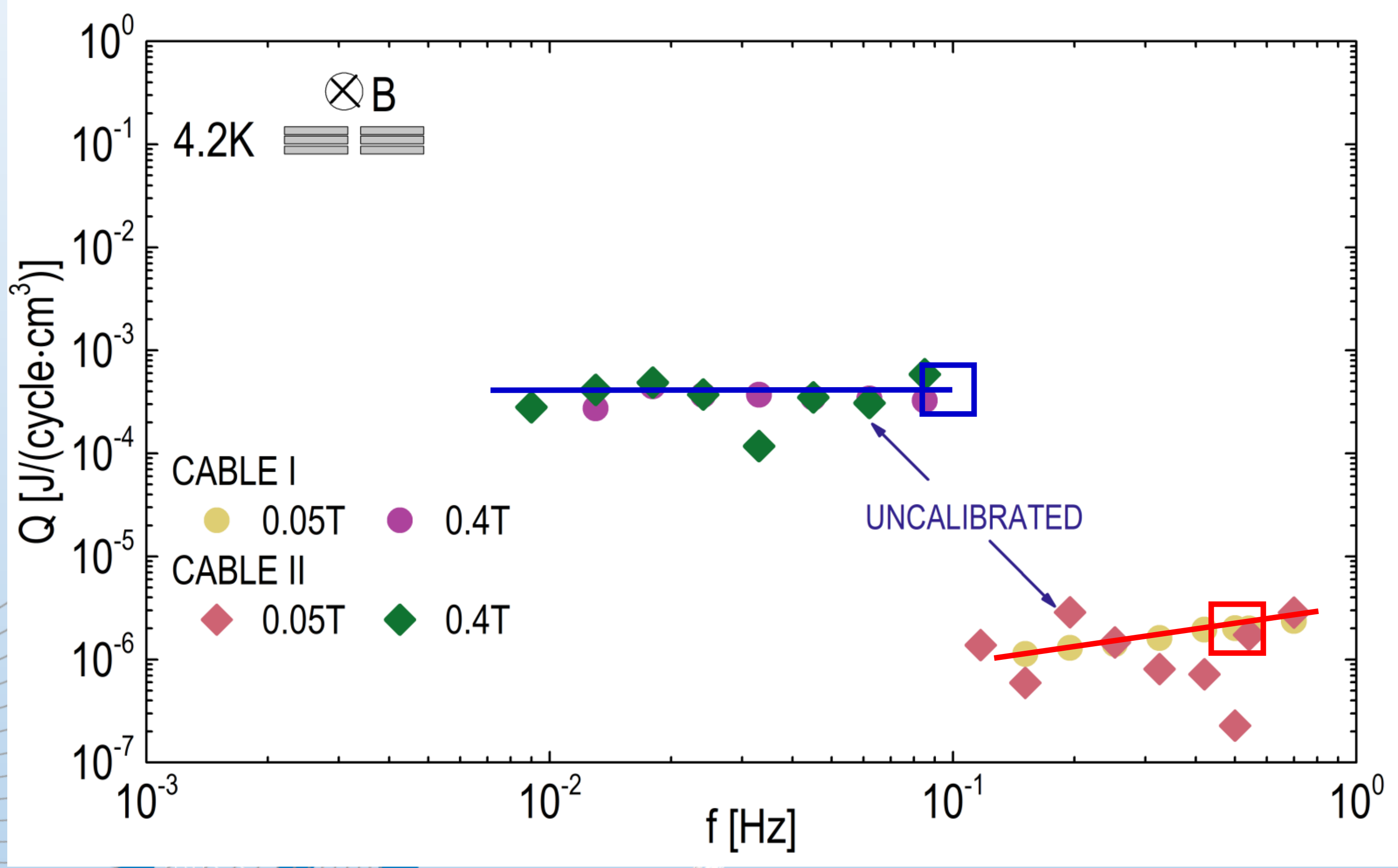
- AC losses are dominated by hysteresis
- Q_h model doesn't fit well with exp. data, but the observed & predicted trends do correspond

4. AC loss @B↑, 4.2K

Amplitude dependence



Frequency dependence



- Coupling losses are observed in the exp. window 5 mT ≤ $\mu_0 H_0$ ≤ 50 mT
- Hysteresis losses are observed in the exp. window 80 mT ≤ $\mu_0 H_0$ ≤ 0.4T
- Modelling: $B_{p\uparrow} \approx 0.11$T

UNIVERSITY OF TWENTE.

Outline of this presentation:

UNIVERSITY OF TWENTE.

1. Motivation
2. Introduction
3. Inter-strand resistance of impregnated Roebel cable
4. AC losses of impregnated Roebel cable
5. **Conclusions**

EMS

5. Summary

UNIVERSITY OF TWENTE.

- R_c of Roebel cables(L_{tp}=226mm) at **4.2 K** is around **1.5 – 10 μΩ**, at **77 K** is about **3 – 20 μΩ**, with about 30% variation within a cable and up to a factor 6 variation from cable-to-cable
- Coupling losses **can be predicted by** using the measured R_c values
- The inter-strand resistance is dominated by the contact resistance of the **Cu-Cu interface**
- AC losses are dominated by **hysteresis @ B⊥**, at 4.2 K, $B_{p\perp} \approx 1$ T ~ 1.7 T
- **Coupling** losses **might be** observed **@ B//** and **B↑**, at 4.2 K, depending on impregnation details; $B_{p//} \approx 0.03$ T
- AC losses @ inclined field mostly (θ ≥ ~ 15º) **dominated** by the **perpendicular** field component
- Analytical models show same trends as measured data, a better fit probably requires numerical modelling

EuCARD-2 is co-funded by the partners and the European Commission under Capacities 7th Framework Programme, Grant Agreement 312453

Thanks for your attention