Magnet diagnostic utilizing stray capacitance monitoring on a 2 m long CCT coil

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*Utilizing **stray capacitance change** for quench detection*

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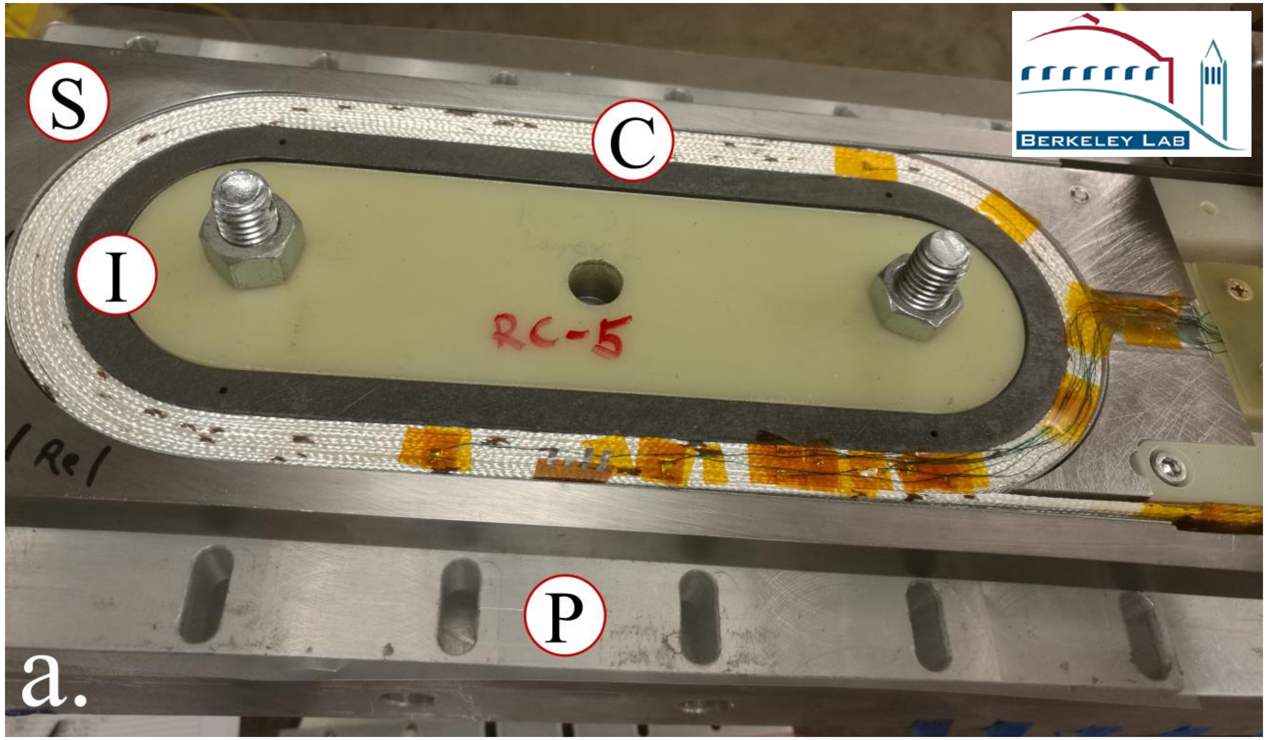
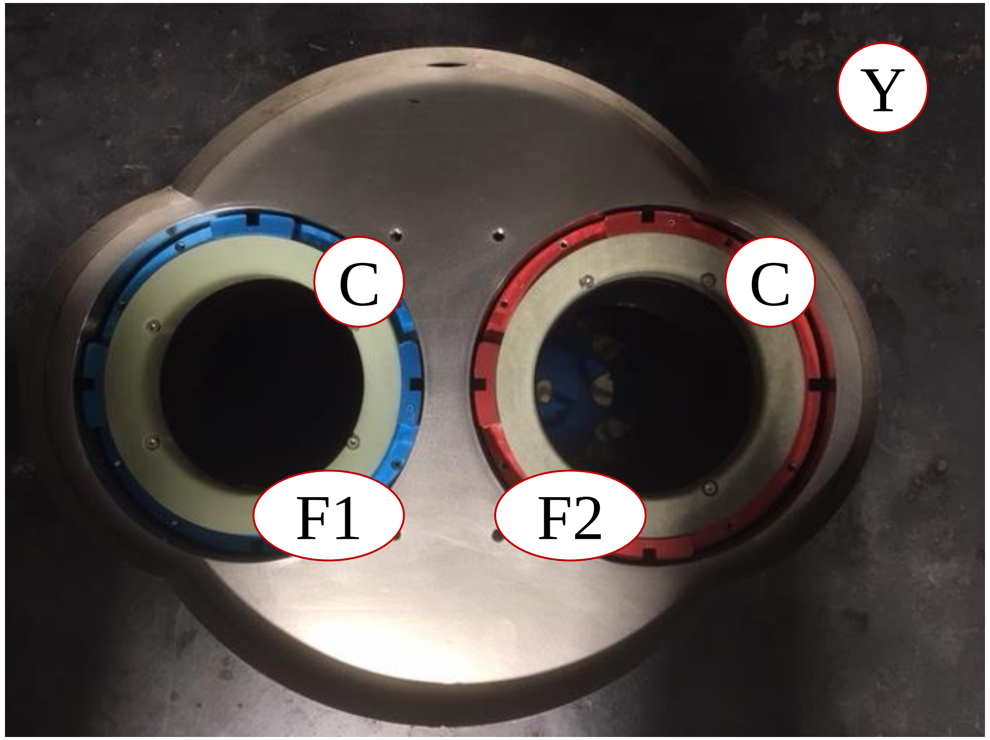
Stray capacitances in magnets…

Any metal component in the magnet structure that is electrically insulated from the others has a certain ***stray capacitance*** *(capacitance to ground or between floating elements)*





Example 1
Coil (C) – Pole island (I) – Horse shoe (S) – Plate (P)

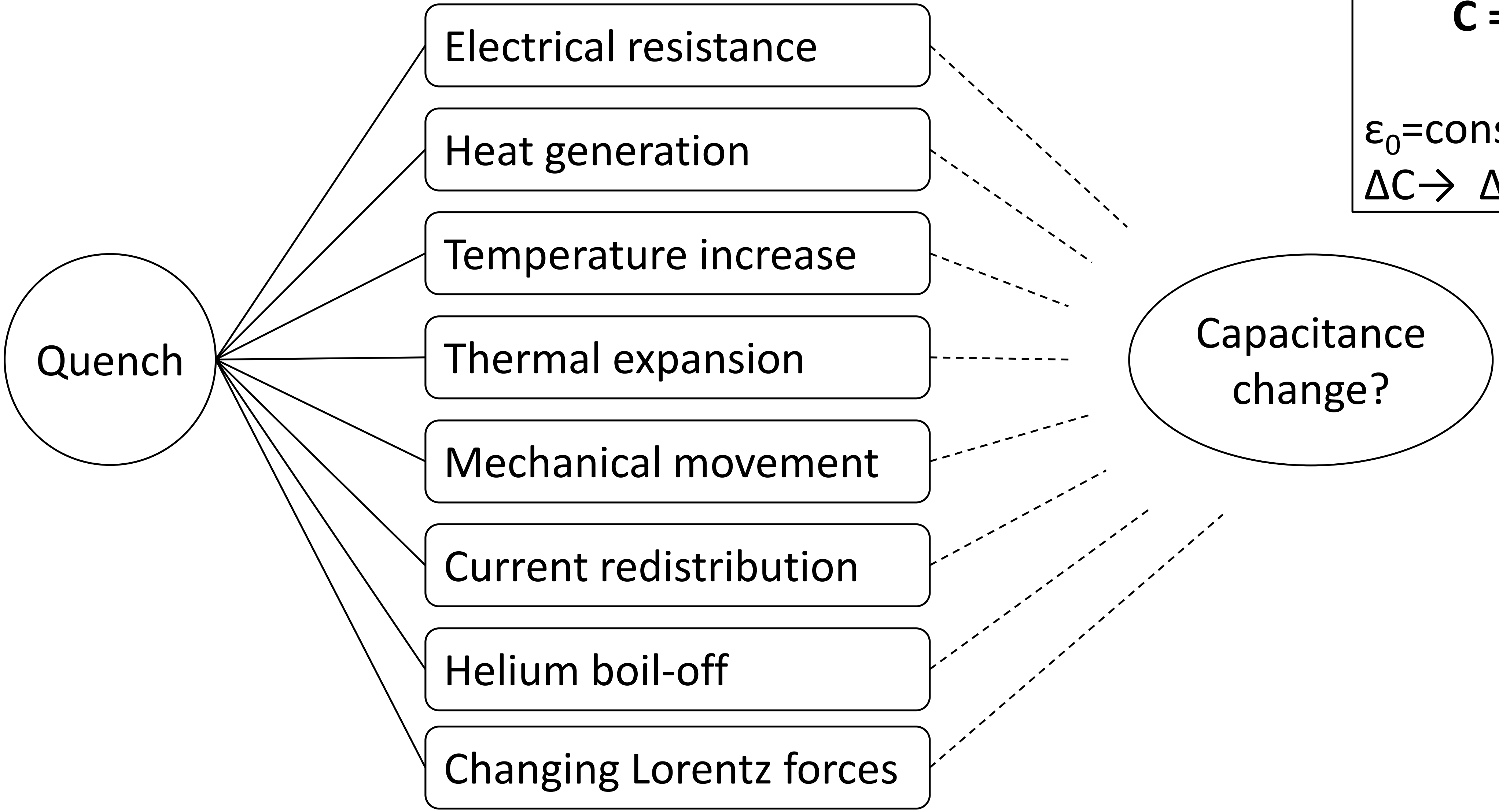
Example 2
Coil (C) – 1st former (F1) – 2nd former (F2) – Yoke (Y)

Stray capacitance change after quench

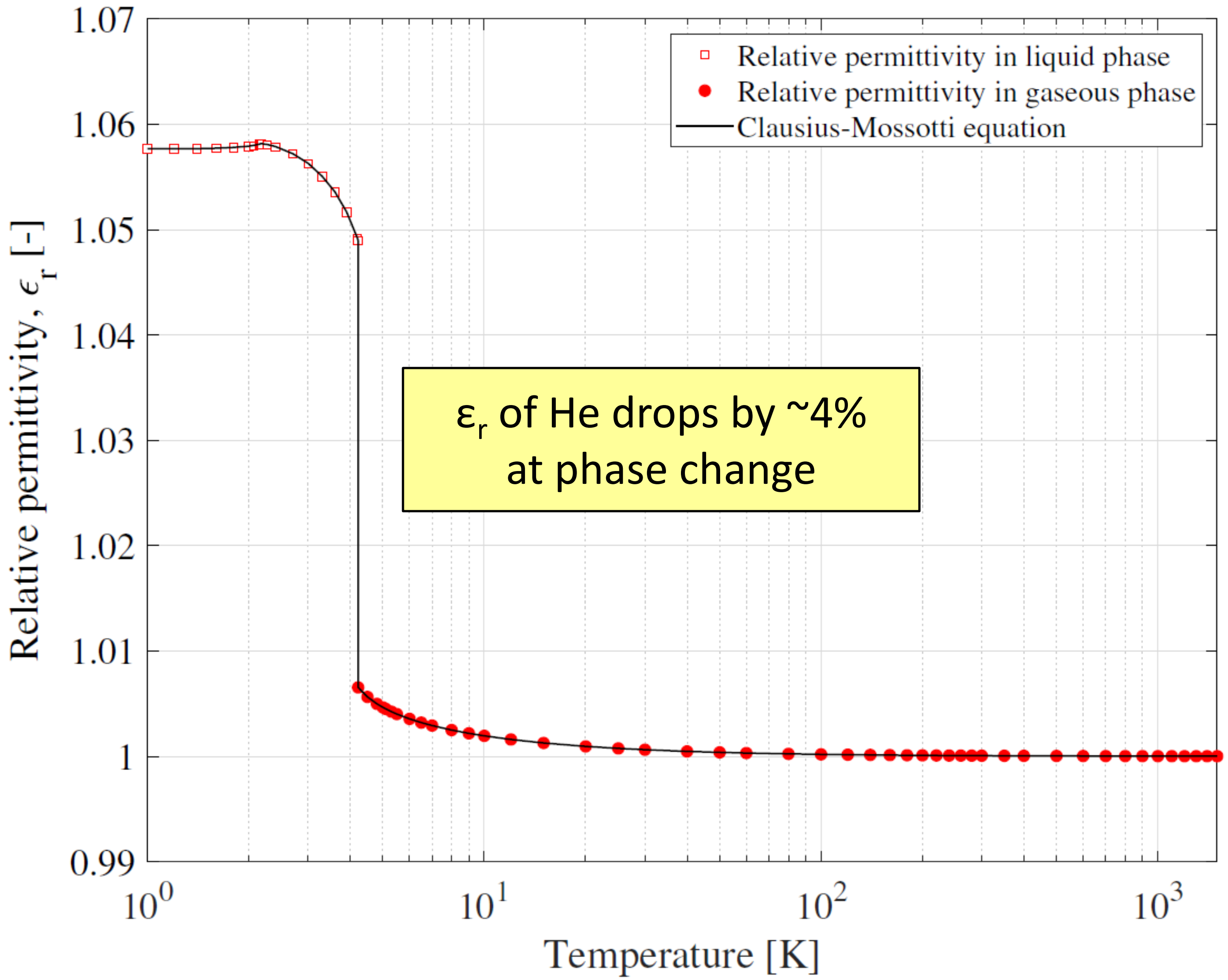
$$C = \varepsilon_0 \varepsilon_r S/s$$

ε_0=const

$\Delta C \rightarrow \Delta\varepsilon_r? \ \Delta S? \ \Delta s?$



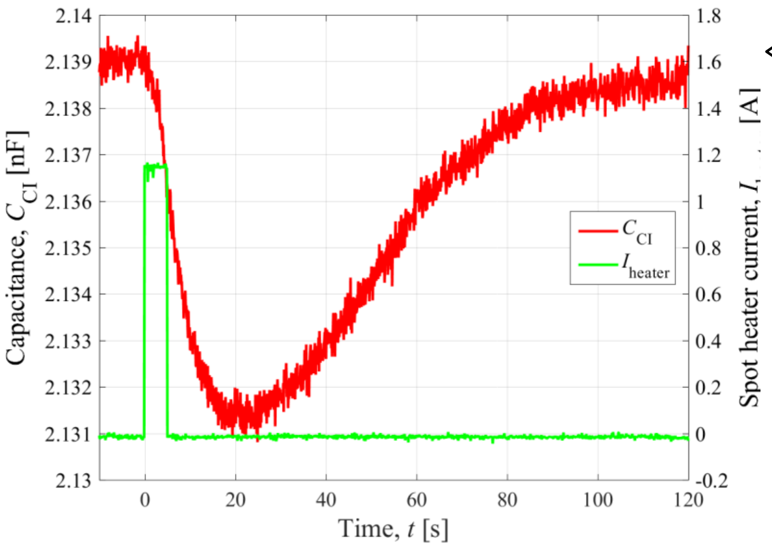
Drop of helium electrical permittivity ε_r at phase change



ε_r of He drops by ~4% at phase change

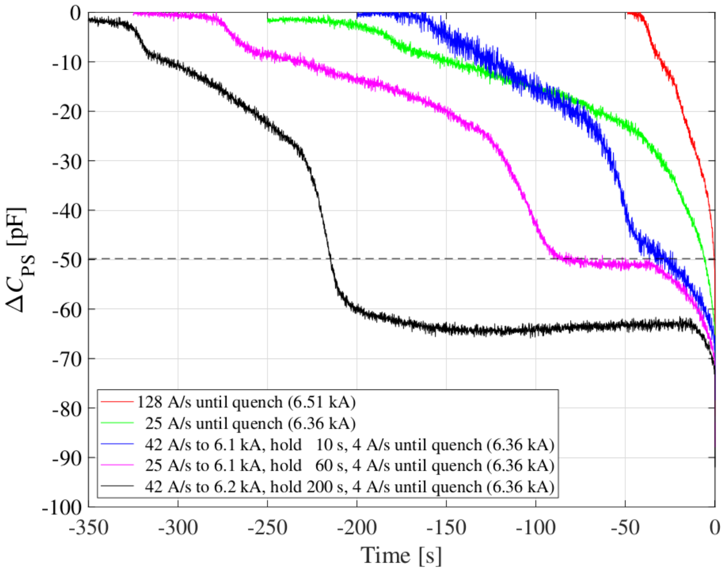
Local heating leads to a stray capacitance drop that can be **detected**

Utilizing ***stray capacitance change*** *for quench detection [**at LBNL**]*



Detection of
localized heat pulses

Detection of
thermal runaways



E. Ravaioli (LBNL→CERN),
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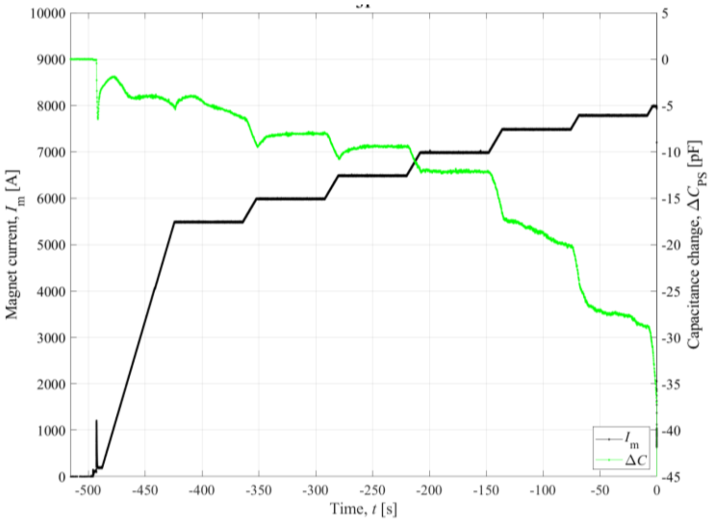
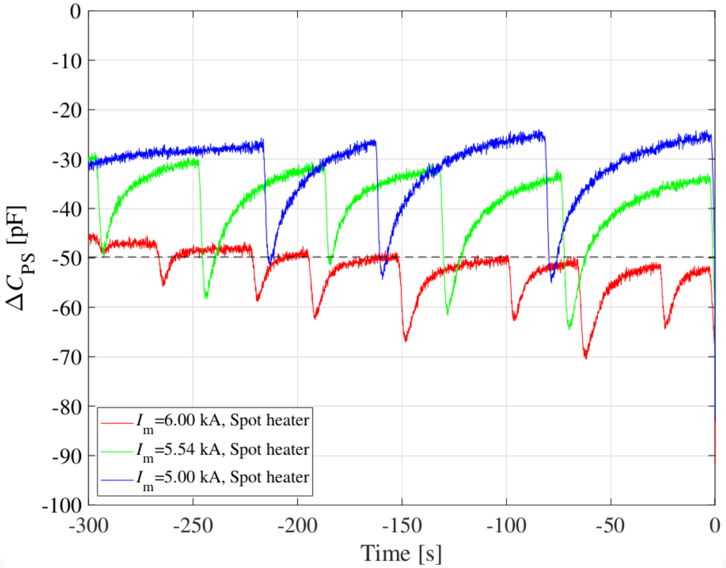
D. Davis (FSU+LBNL), K. Zhang (LBNL→PSI)
[1] IEEE Trans. Appl. Super., 2017
[2] Physica Scripta 2019
[3] D. Davis, MT26 → Wed-Af-Or13-03



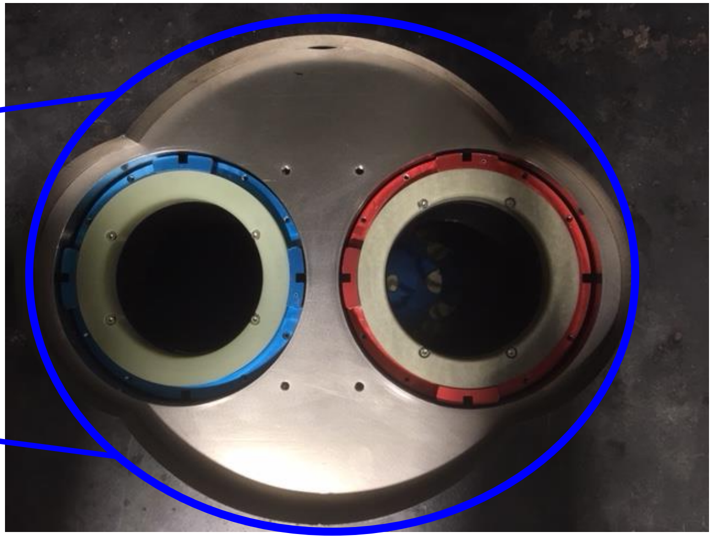
Detection of ohmic losses
in current sharing regime

Detection of
induced quenches

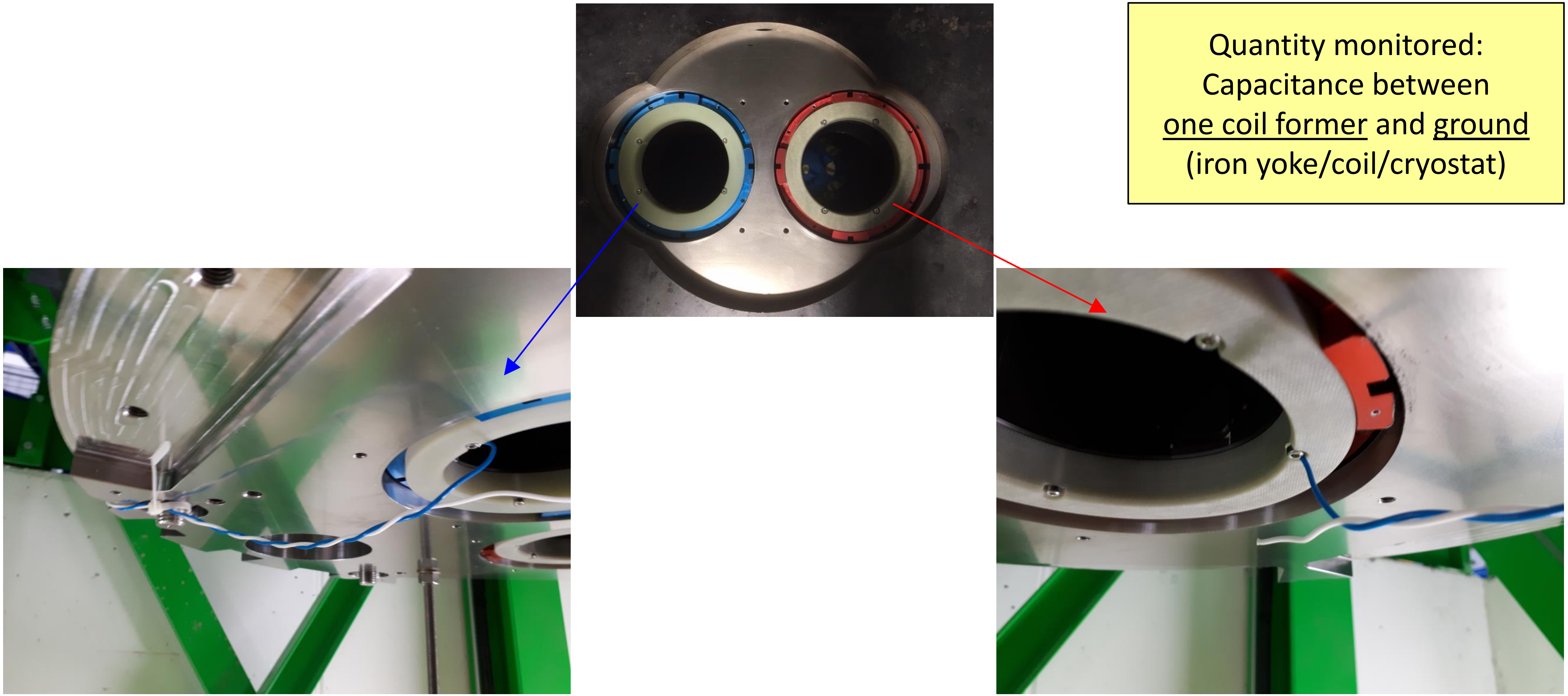


2-aperture, 2 meter long, Nb-Ti CCT coil for HL-LHC [at CERN]

Quantity monitored:
Capacitance between
one coil former and ground
(iron yoke/coil/cryostat)

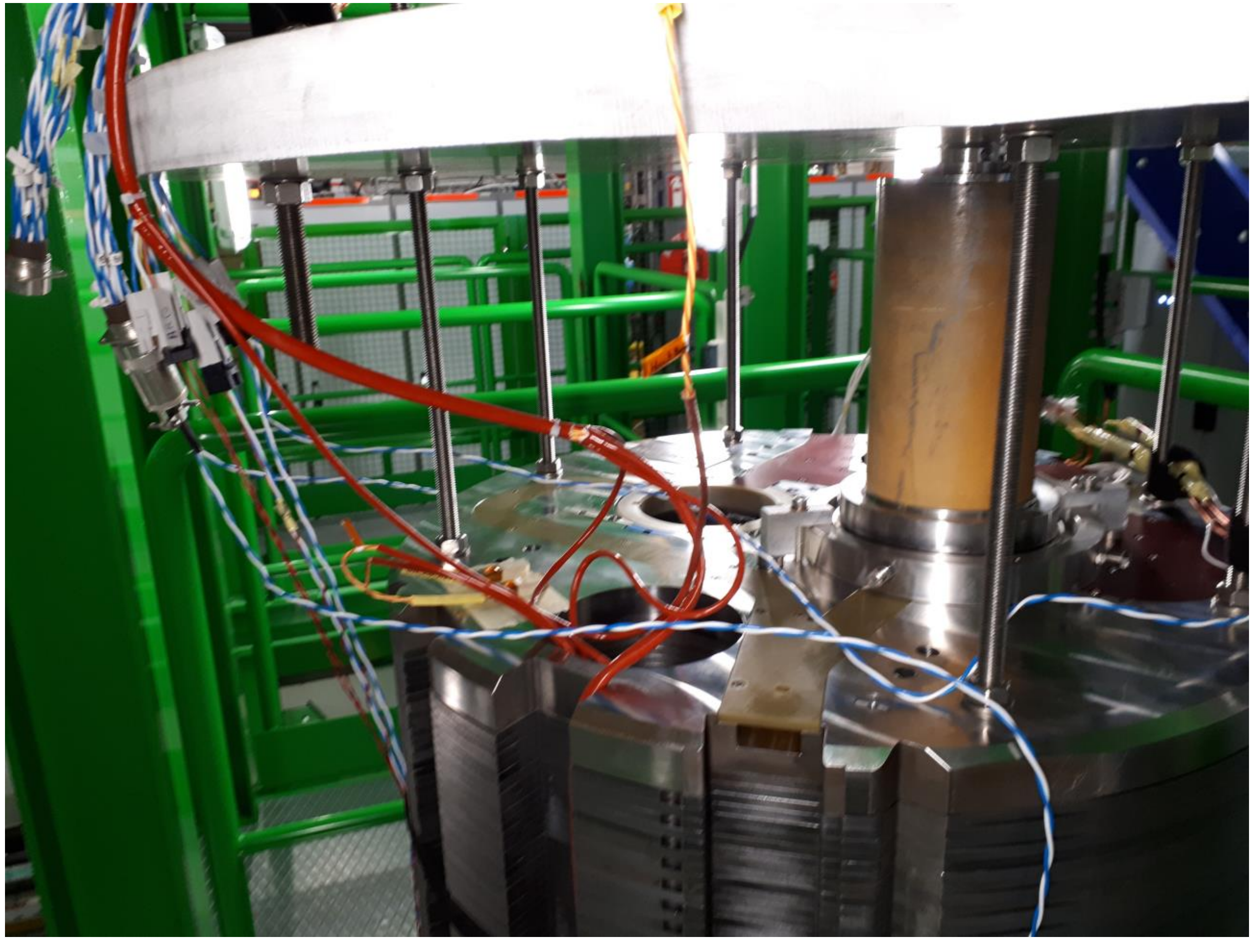


Taps connected to the two coil formers



Quantity monitored:
Capacitance between
one coil former and ground
(iron yoke/coil/cryostat)

Routing of the taps



CERN capacitance monitoring system – HW

The system was designed and installed by K. Stachon and M. Bednarek (CERN).

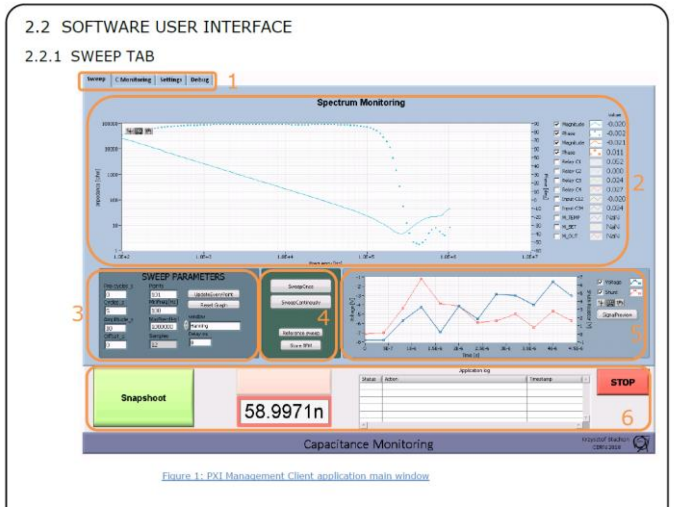
Applied high-frequency, low voltage AC signal

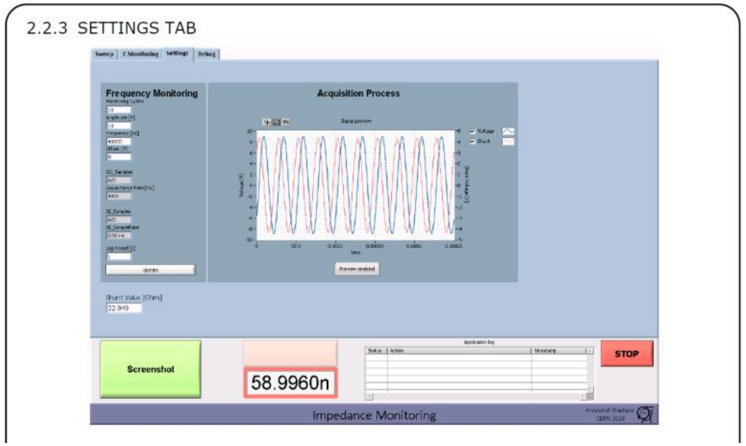
Voltage and current measurement

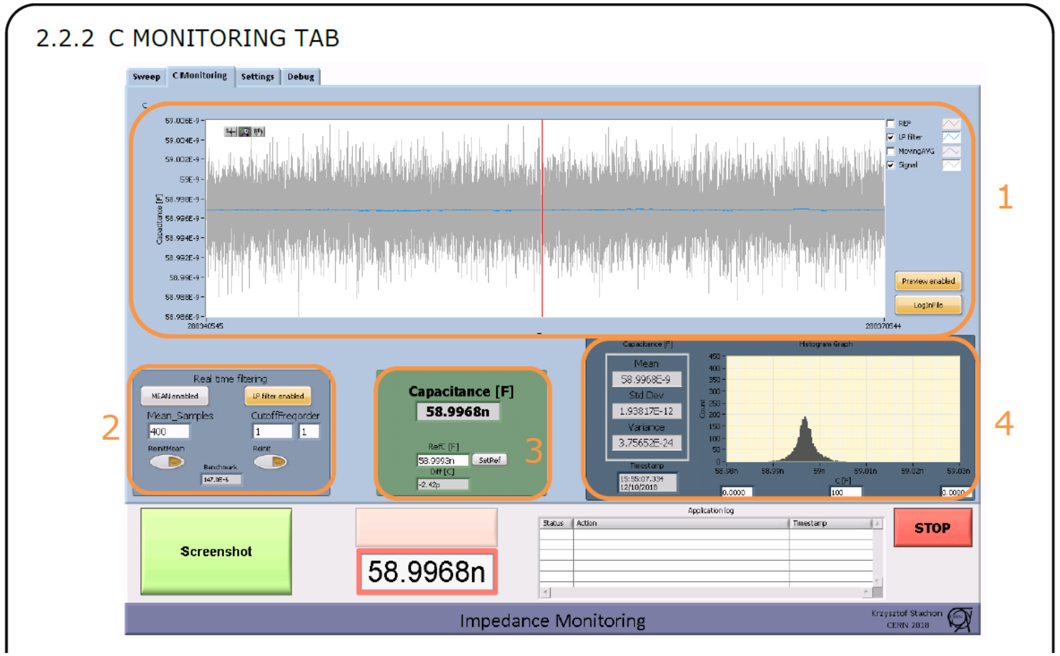
Voltage tap connection

CERN capacitance monitoring system – SW

The system was designed and installed by K. Stachon and M. Bednarek (CERN).







Frequency transfer function

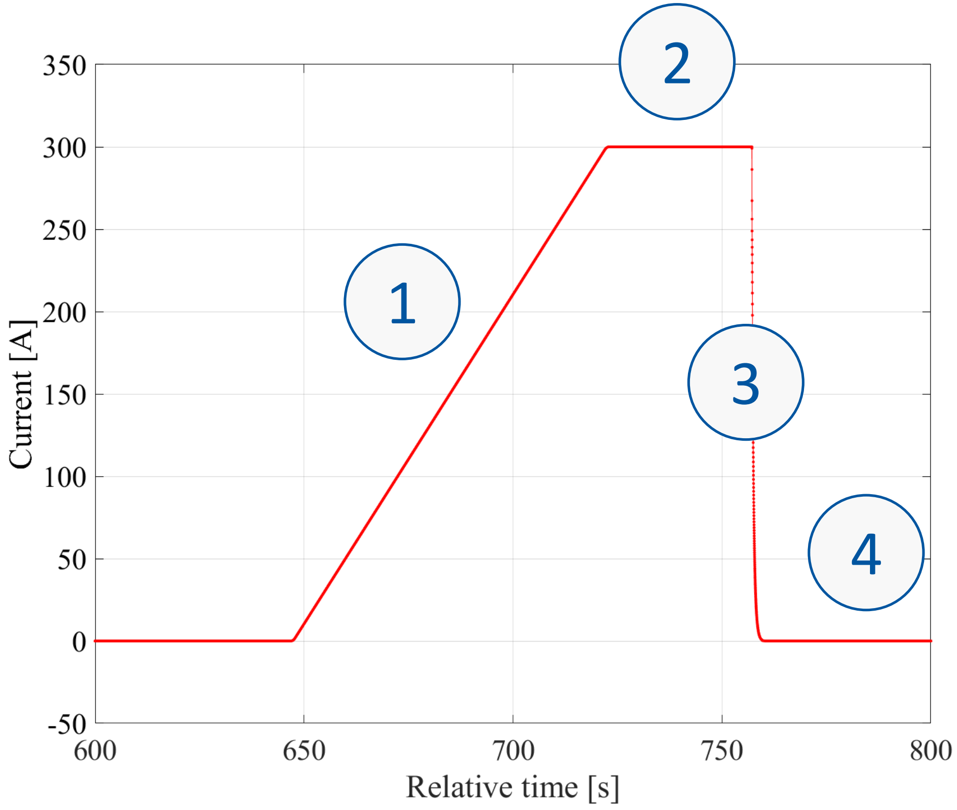
AC signal settings

Online capacitance monitoring

When measuring a capacitance of tens of nF:
→ Noise **<2 pF** with acquisition frequency of **4 kHz**
→ Noise **<0.2 pF** with acquisition frequency of **10 Hz**

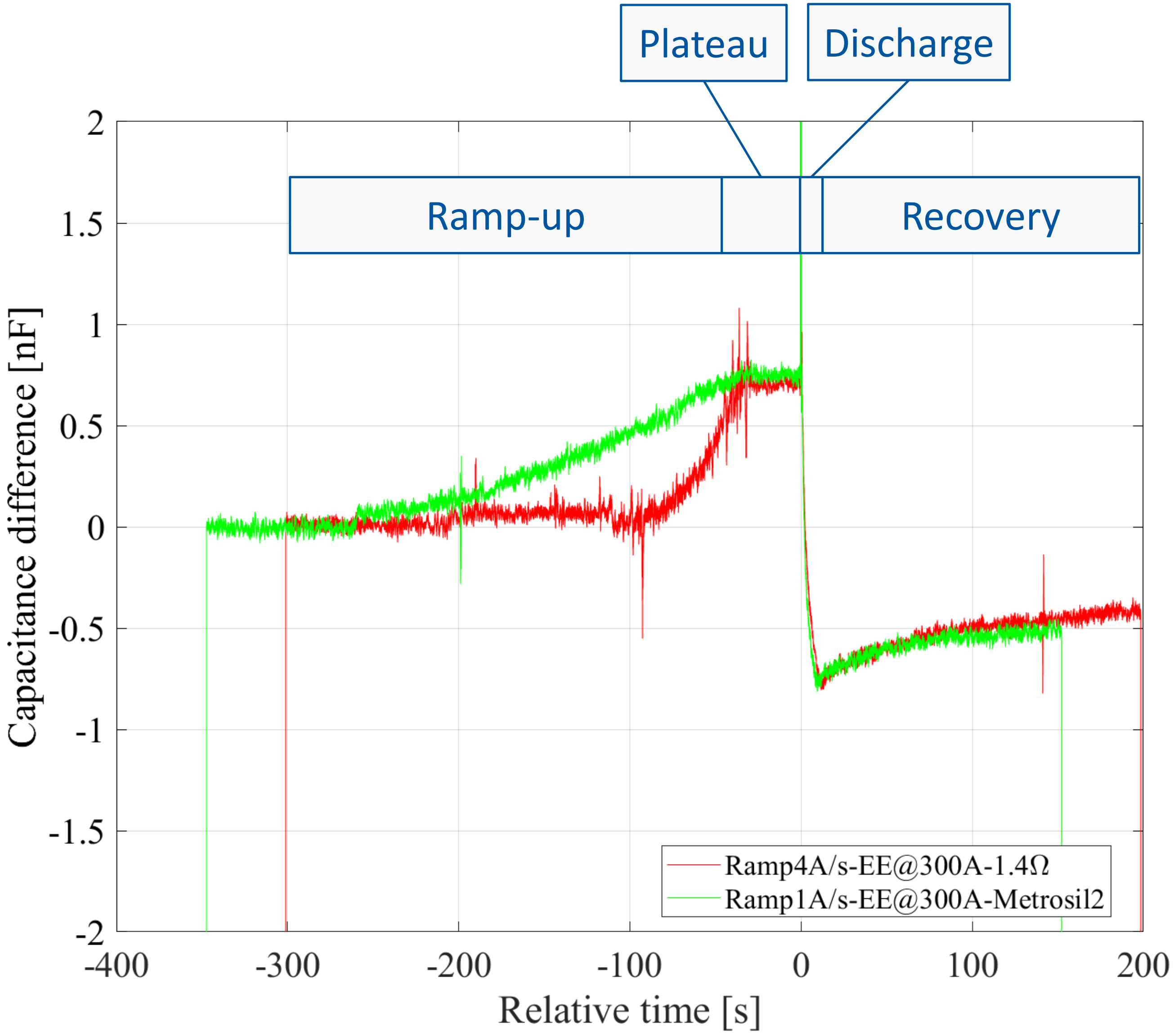
What we expect during an energy-extraction test

1. Ramp-up
2. Plateau
3. Energy-extraction discharge
4. Recovery



1. Lorentz forces, low heating
2. No change
3. Fast heating (quench back)
4. Recover initial state

Capacitance monitoring during two typical tests



Ramp-up
Squeezing of insulation layer between coil and former
→ ΔC increase [**C** ≈ ε_0 ε_r S/**s**]

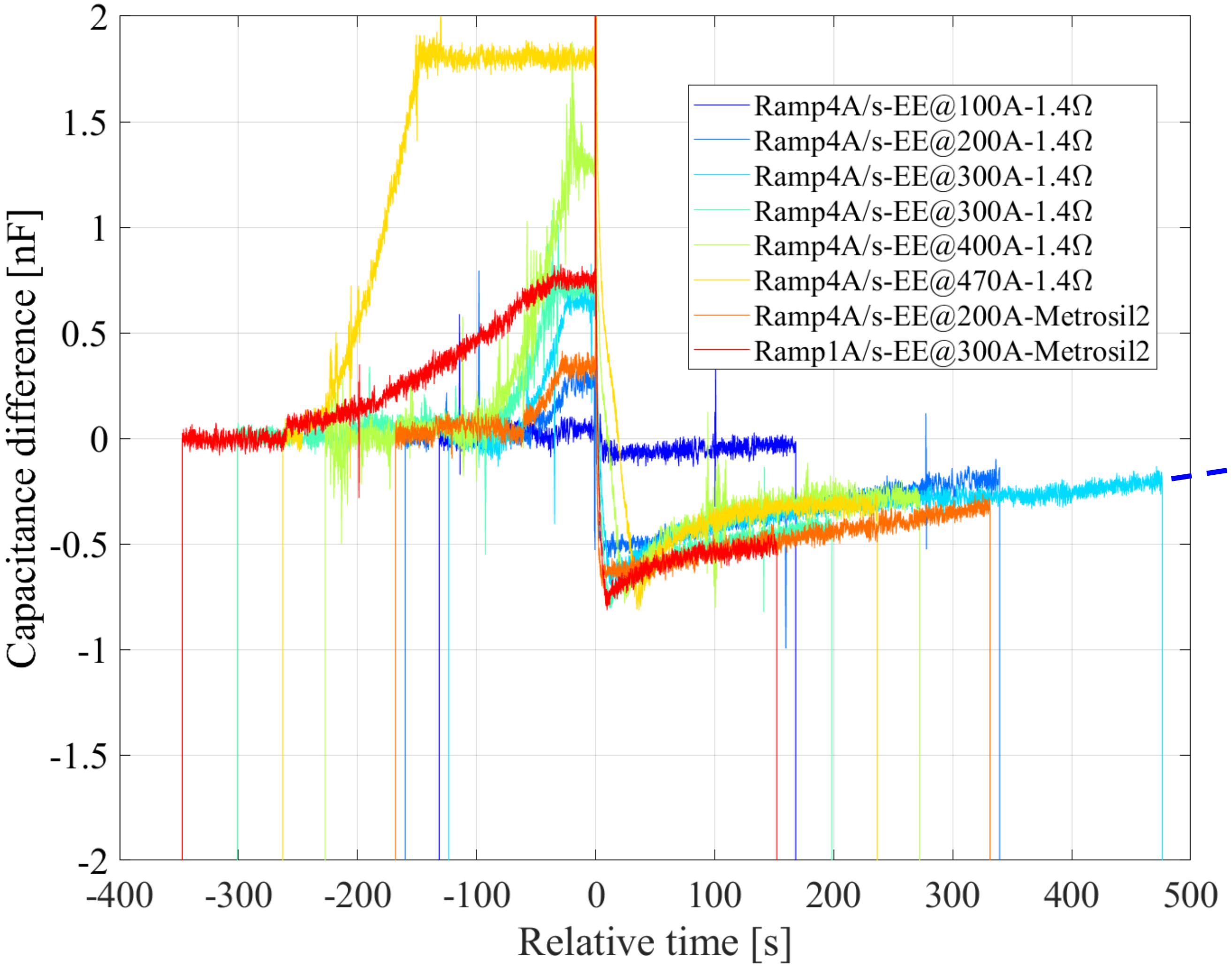
Plateau
No change

Discharge
Fast heating (quench back) and Lorentz forces disappear
→ Fast ΔC decrease [**C** ≈ ε_0 $\boldsymbol{\varepsilon_r}$ S/s]

Recovery
Back to initial capacitance value
ΔC→0

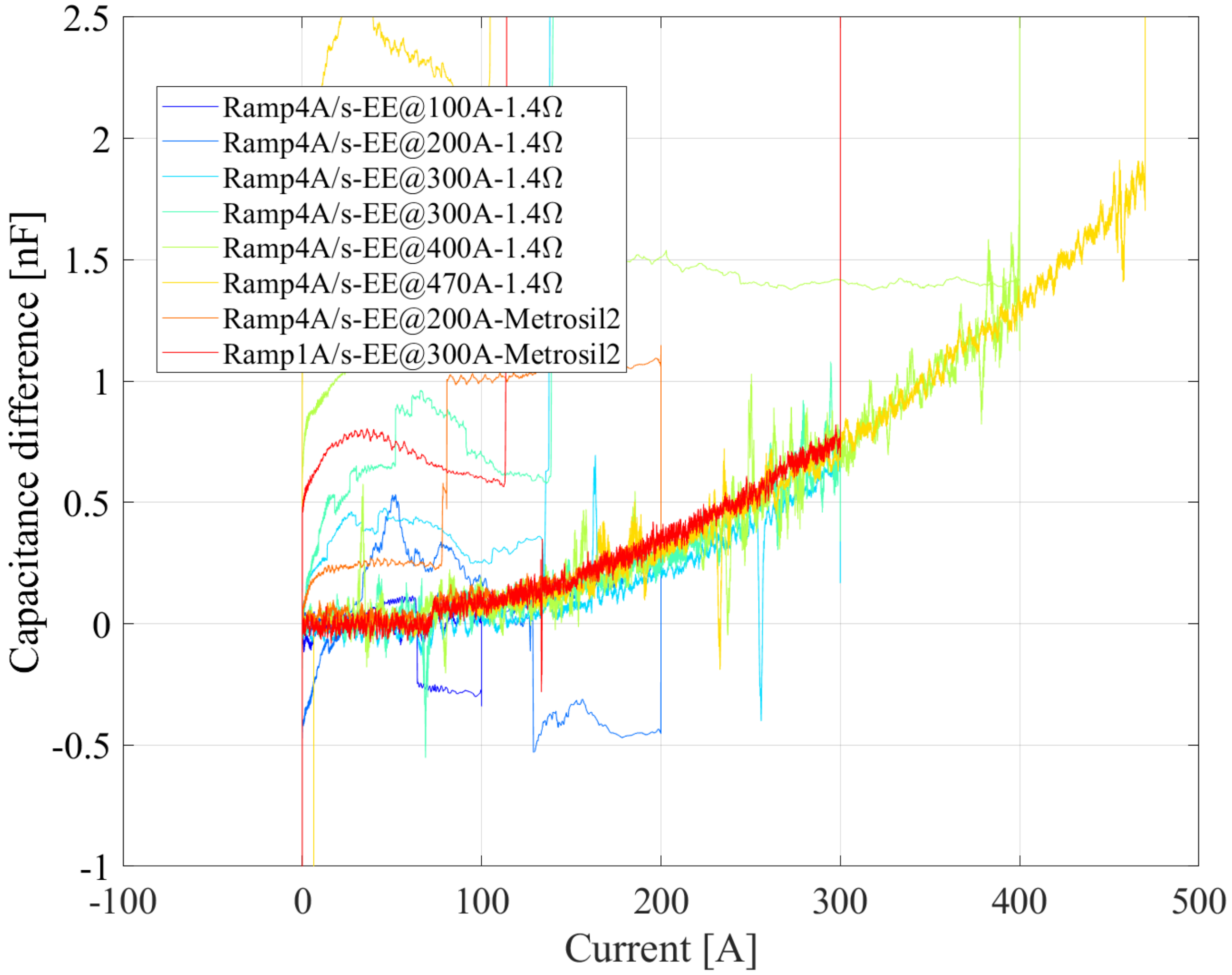
Tests at different current levels (100-470 A)

Ramp-up → Plateau → Discharge → Recovery



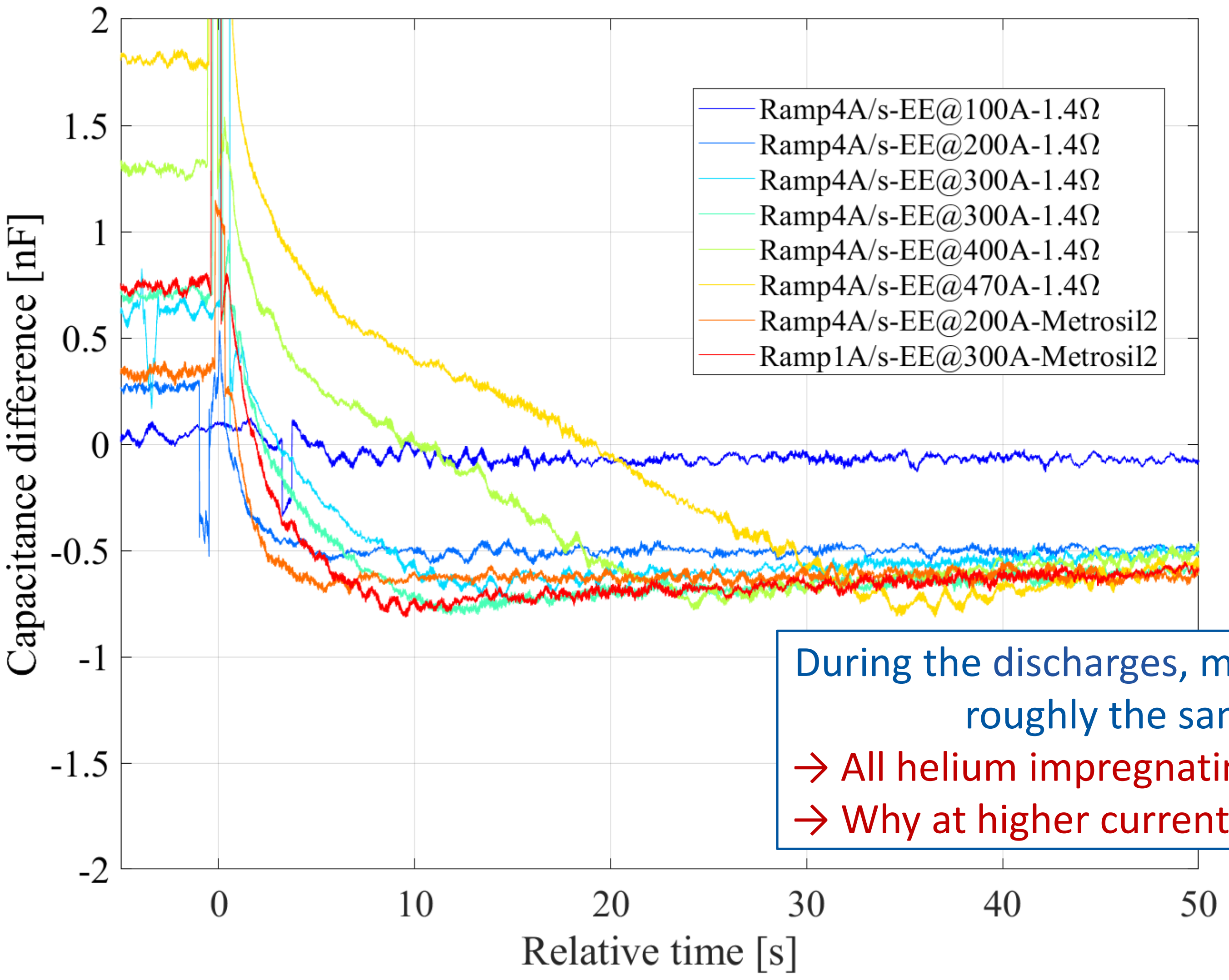
After the discharges, the capacitance returns to the original value in tens of minutes (!) →Why?

Measured capacitance difference versus current



During the ramp-ups, capacitance change is roughly proportional to the square of the current
→ Lorentz force contribution

Capacitance change during the discharge (zoom)



During the discharges, minimum capacitance change is roughly the same in all tests >100 A

→ All helium impregnating the insulation evaporates?

→ Why at higher current C changes more slowly?

Conclusion

Stray capacitance change monitoring

→ Relatively **unobtrusive** technique that can be provide complementary diagnostic
→ Measurement system is **fast** enough, **precise** enough
→ [only in HTS coils] High heating was consistently detected **hundred of ms or seconds** before actual quench
→ **Different physical phenomena** were successfully observed/detected at LBNL and CERN

- Change of **phase** and cryogenic conditions during warm-up
- Transitory **losses** during ramp-ups ("AC losses")
- Ohmic loss in the conductor in **current-sharing regime**
- Ohmic loss in the conductor after **quench** (thermal runaway)
- Ohmic loss in the **splices**
- Heat deposited by **external heaters**
- **Lorentz forces** during ramp-ups

Potential applications

→ Pre-quench heating **detection in HTS coils**
Heating was consistently detected hundred of ms or seconds before actual quench
→ Information about magnet **mechanical features**
Capacitive strain gauges were used already decades ago
→ Information about **liquid He** level in the coil
→ **… … … … …**

The next step

Dedicated sensors with well-known size and features, purposefully built for one function
→ More sensitive to **one** physical phenomenon
→ **Localization**

QUESTIONS?

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Annex

Monitored powering tests

Ap1	Ap2	Ramp dI/dt [A/s]	I [A]	EE	Comments
X		4	100	Resistor	
X		4	200	Resistor	
X		4	200	Metrosil	
X		4	300	Resistor	
X		4	300	Resistor	Repeated
X		4	400	Resistor	
X		4	470	Resistor	
X		1	300	Metrosil	Slower ramp-up
X		4	300	Metrosil	Different monitoring frequency
X		4	300	Metrosil	Different monitoring voltage
	X	4	200	Metrosil	No ΔC since Ap2 is not monitored
	X	4	300	Metrosil	No ΔC since Ap2 is not monitored
	X	4	350	Metrosil	No ΔC since Ap2 is not monitored
	X	4	400	Metrosil	No ΔC since Ap2 is not monitored
X	X	4	400	Metrosil	Both apertures powered