High-Q Operation of SRF Cavities:

The Impact of Thermocurrents on the RF Surface Resistance

J. Vogt, O. Kugeler, J. Knobloch, Phys. Rev. ST Accel. Beams 18, 042001 (2015)

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Helmholtz-Zentrum Berlin

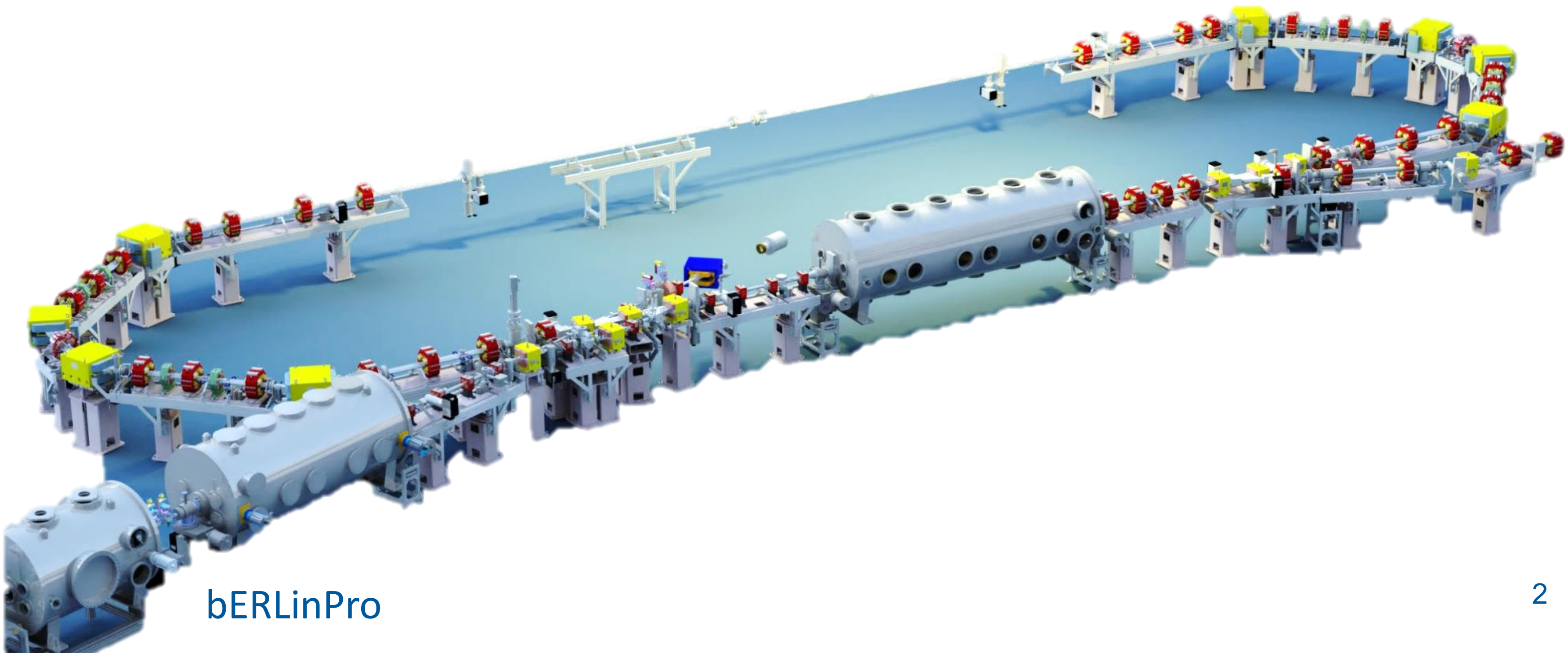
17th International Conference on RF Superconductivity

September 13-18, 2015, Whistler, Canada

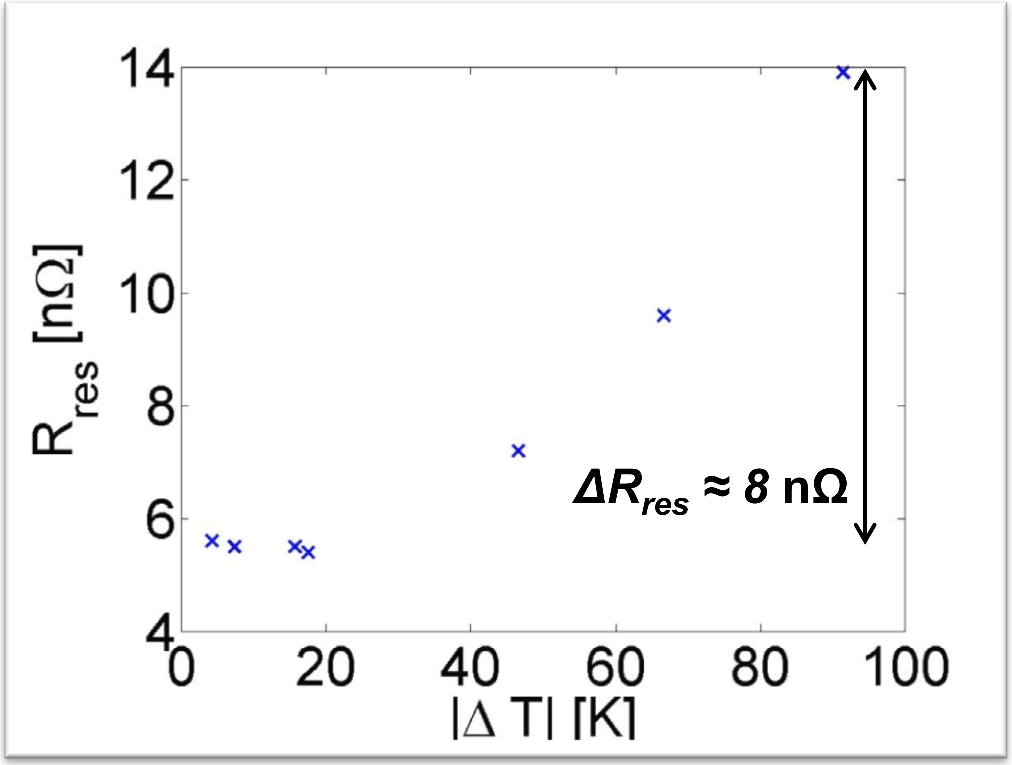
Why bother?

- Demand for high duty cycle or **cw beams** in modern application (LCLS-II, XFEL, bERLinPro…)
- Elevated **dynamic losses**
- Refrigeration efficiency ≈ 1/1000

  → **Minimization of power loss and costs**
- BCS resistance decreases with temperature, residual resistance not
- General interest in understanding loss mechanisms in sc cavities



Status SRF 2013:
Cooling conditions and thermal cycle can significantly impact and degrade the quality factor



- Thermal cycle can decrease as well as increase the residual surface resistance (low ambient magnetic field)

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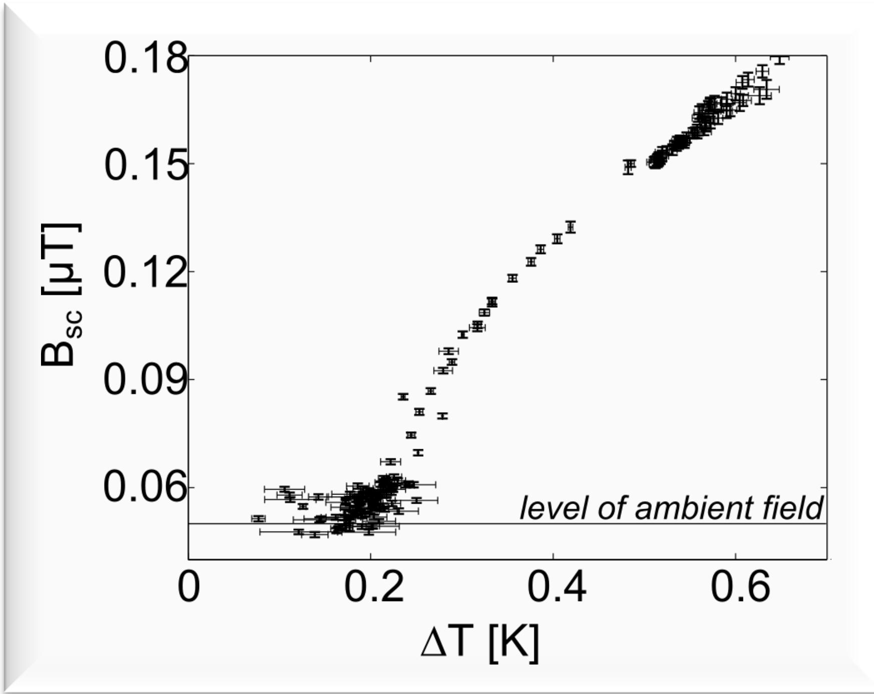

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- Sample test indicate major impact of cooling dynamics (gradient/rate) on flux expulsion

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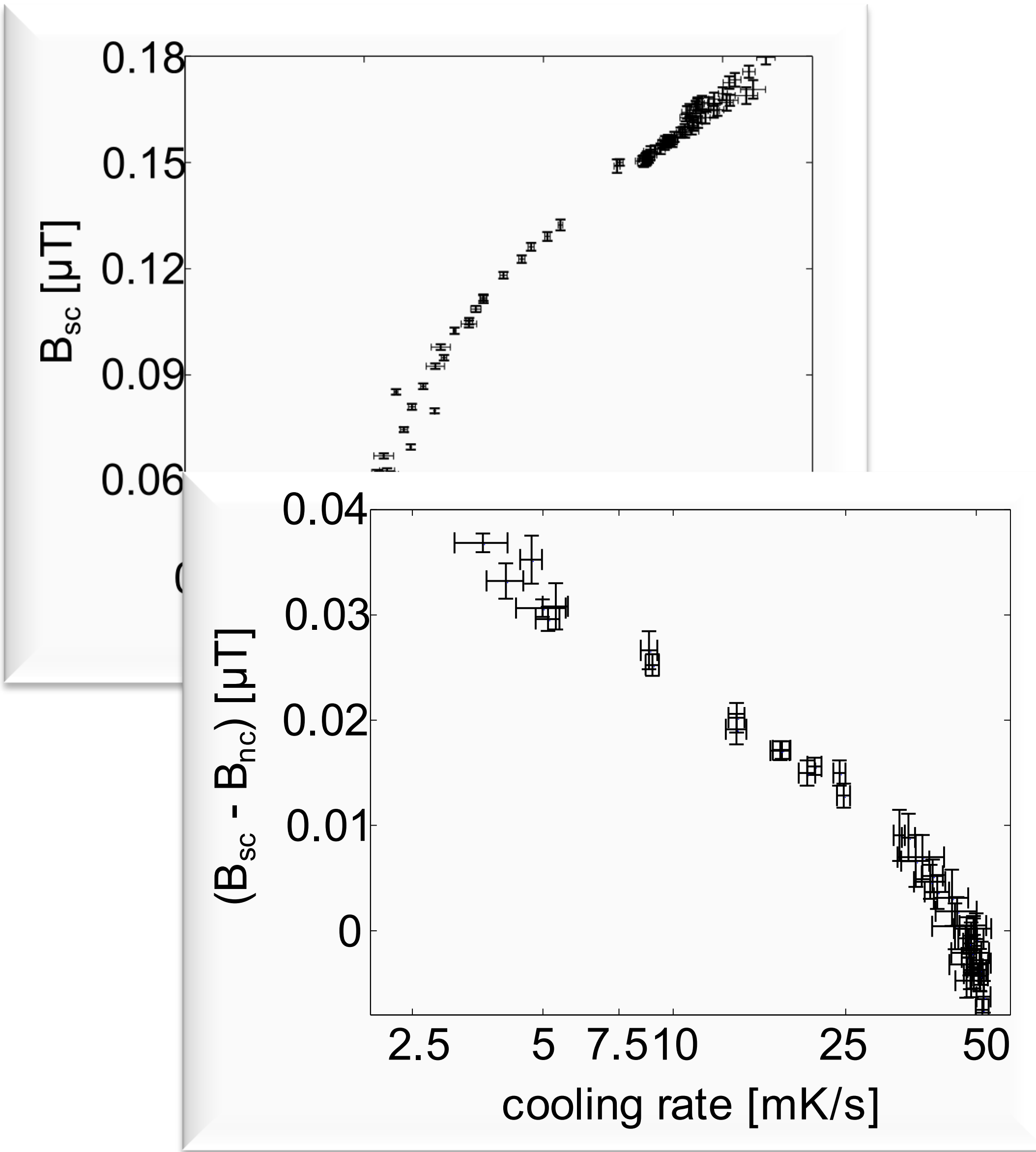

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Thermocurrents   Flux expulsion

Aull et al., PRSTAB 15, 062001 (2012)

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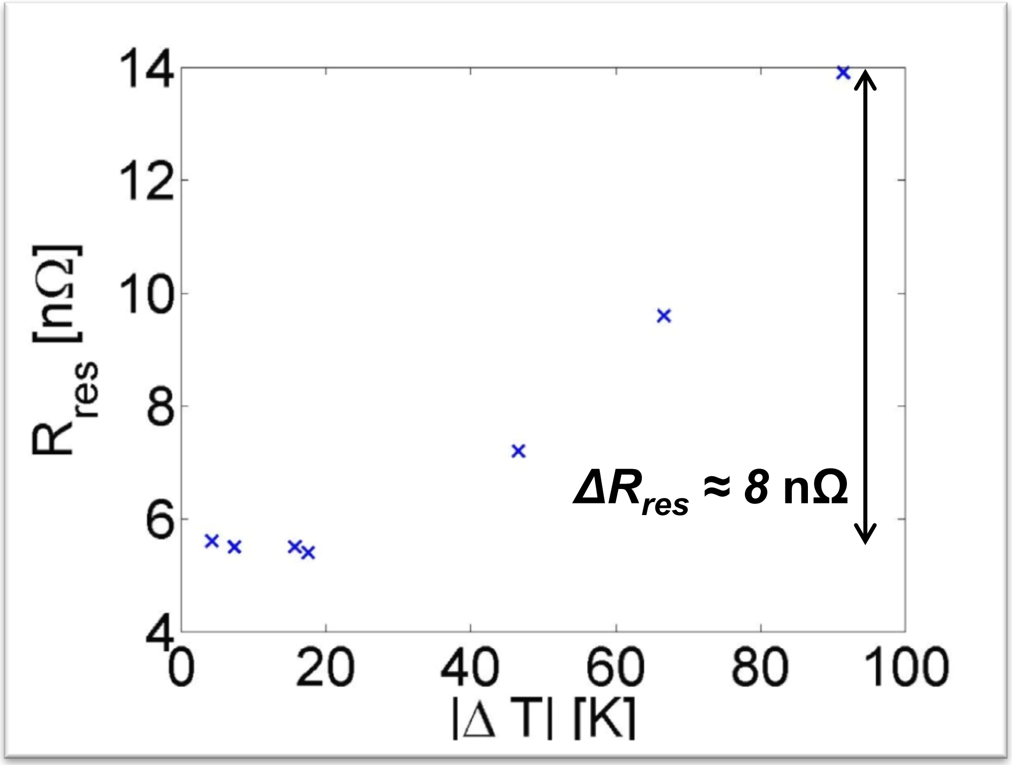

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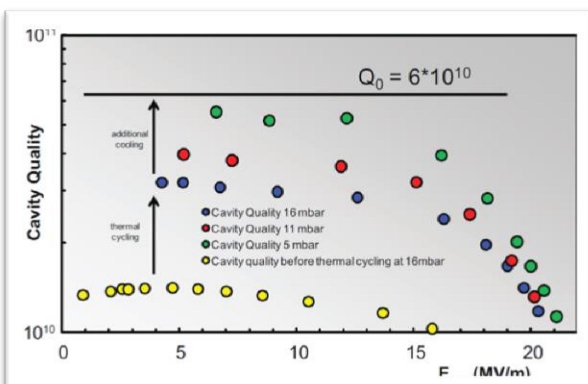

- First reported 2009

  O. Kugeler et al.,
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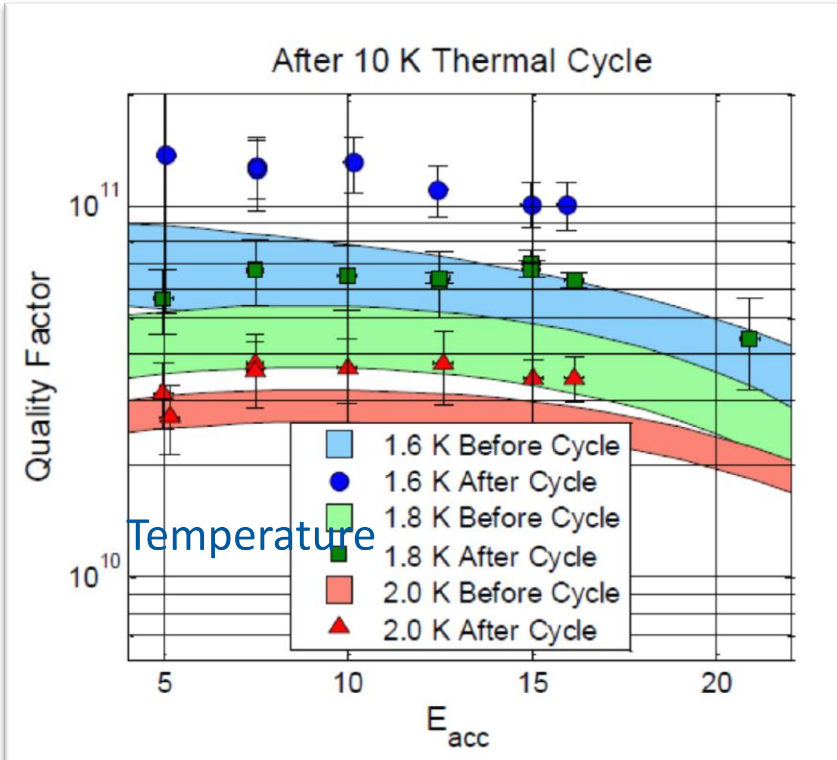
Status SRF 2013:
Cooling conditions can significantly impact and degrade the quality factor
Cornell confirmed: Thermal cycle improves Q
Courtesy R. Eichhorn



Time

- After a 10 K thermal cycle significant increase in the Q (up to a Q of $6 \cdot 10^{10}$ design operation parameters being three times higher than targeted)
- measurements suggest that effect is related to magnetic fields

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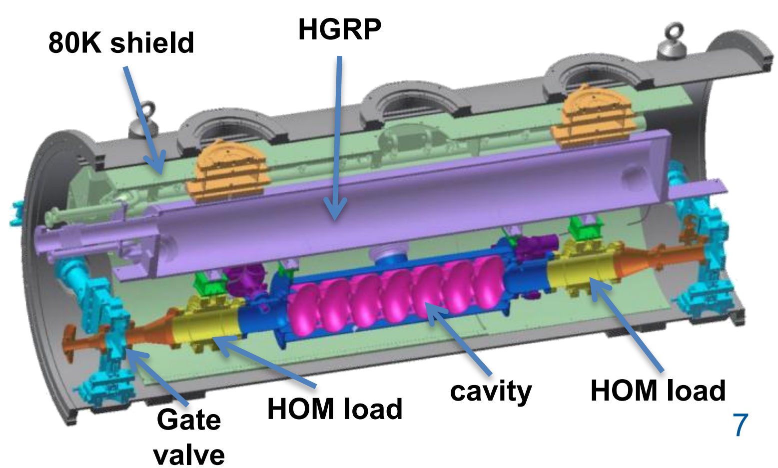

Remark: only one flux direction was measured

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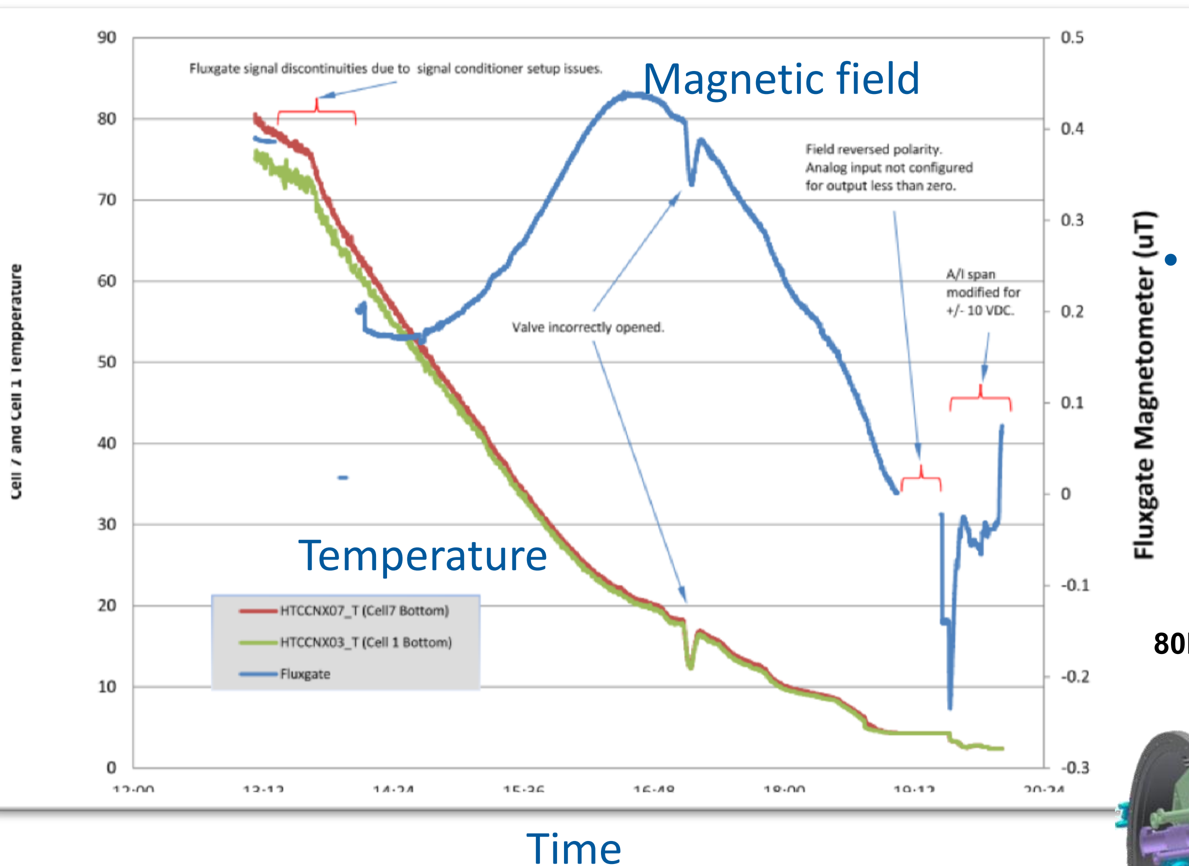

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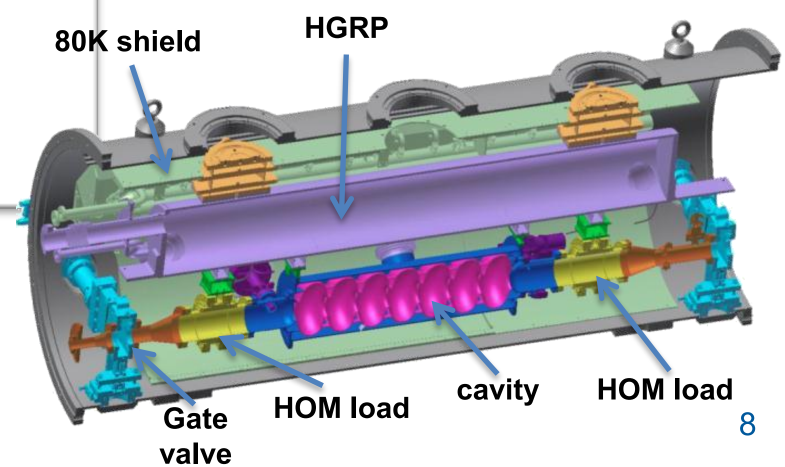

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Status SRF 2013:
Community still in doubt if thermocurrents are origin of that magnetic flux

Open questions:

1. More detailed study of the impact of **temperature difference** on the **surface resistance**
2. Exact **Seebeck coefficients** in the temperature regime of interest to analyze magnitude of thermocurrents
3. **Geometry and distribution** of thermocurrents
4. Direct measurement of the **magnetic field** in the cavity tank system and especially on RF surface

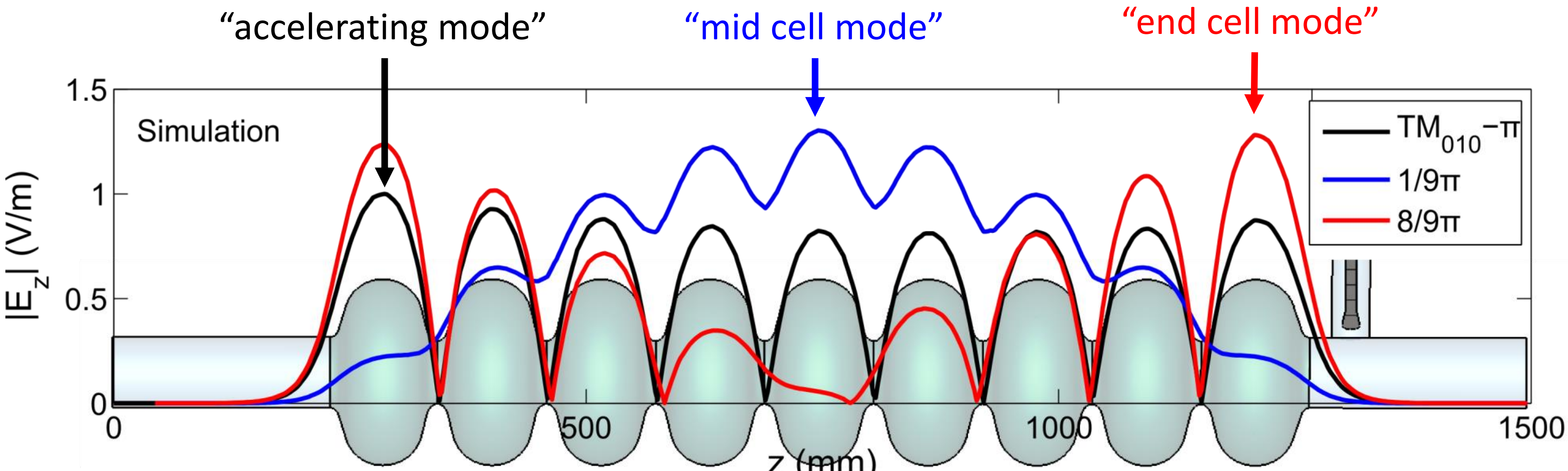
1. More detailed study of the impact of **temperature difference** on the **surface resistance**

$$R_S(T) = \boxed{A \cdot \exp\left(\frac{-B}{T}\right)} + \boxed{R_{res}} = G/Q_0$$

BCS resistance is the same for all modes (at fixed E_{acc}), depends on T

Depends on amount of trapped flux but not on T

G_π = 271.2 Ω
$G_{8\pi/9}$ = 271.5 Ω
$G_{\pi/9}$ = 268.3 Ω
$A = (31.8 \pm 2.2)\ \mu\Omega$
$B = (15.7 \pm 0.2) K$



Courtesy Axel Neumann

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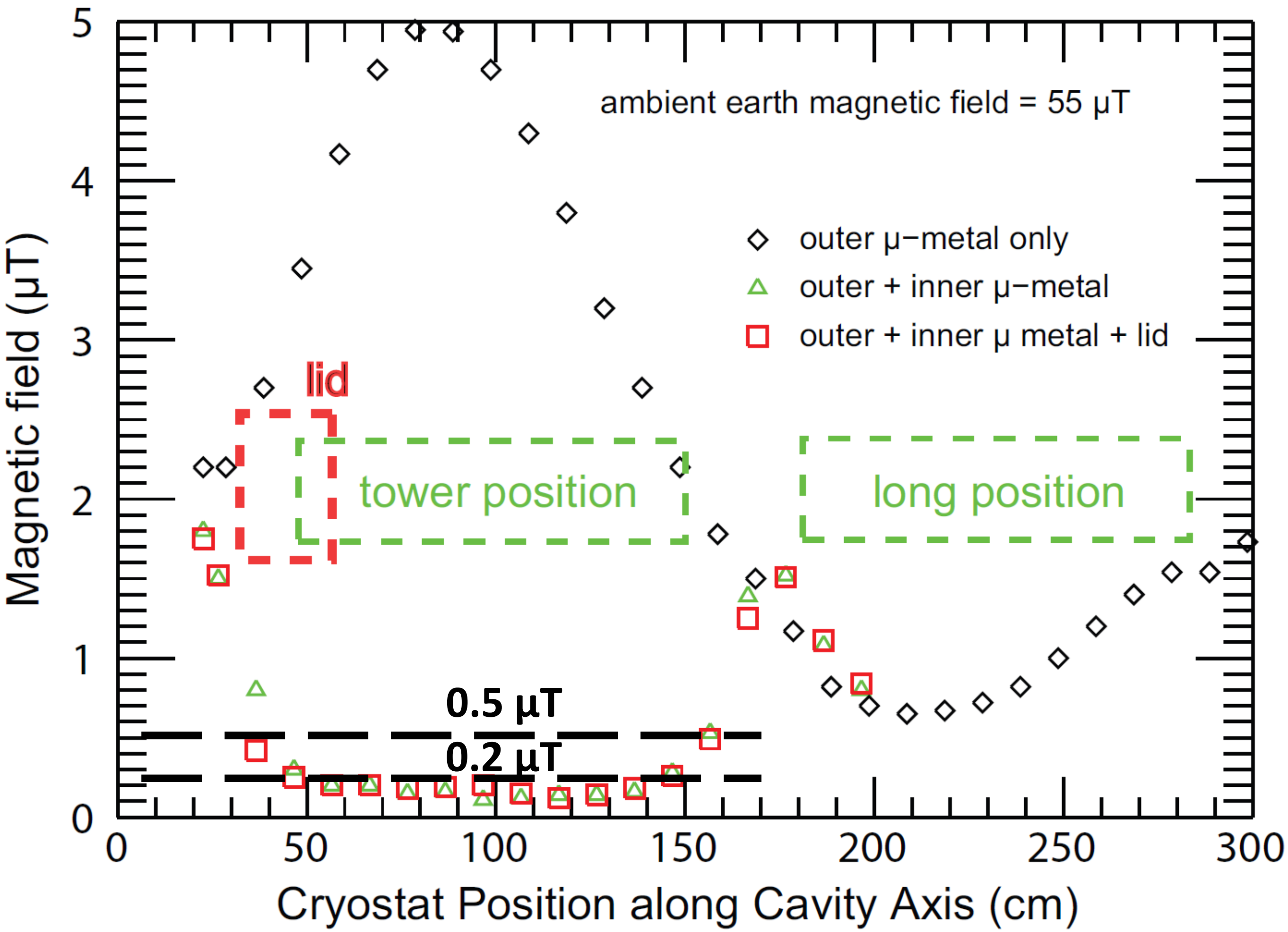

Ambient field in the HoBiCaT cryostat:

- less than 0.2 µT at the center cells
- about 0.5 µT maximum in the end cells

Evaluation of $\langle \mathbf{R}_{\mathbf{res}} \rangle$ and hence **the change in trapped flux** in different cells of the cavity

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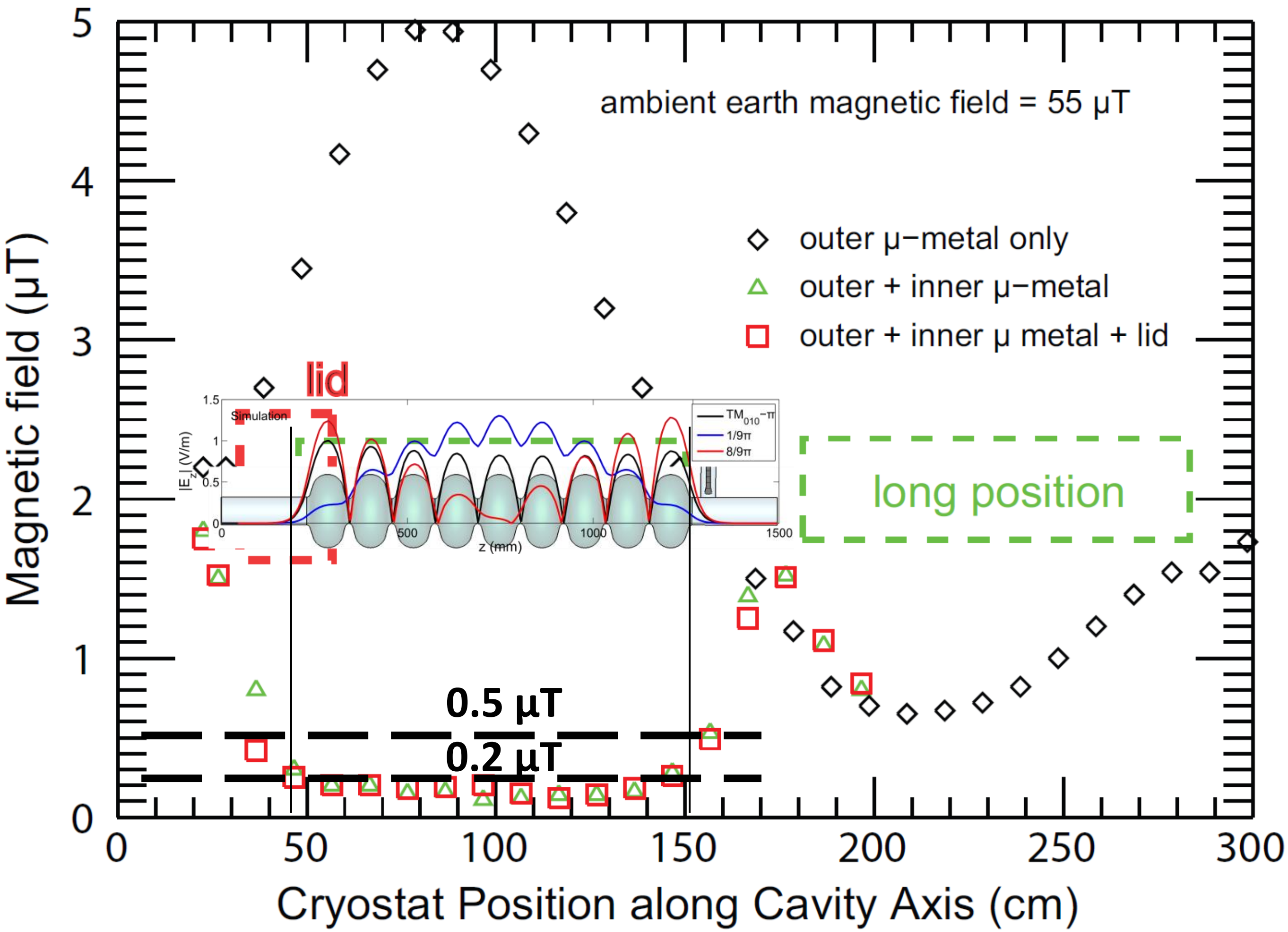

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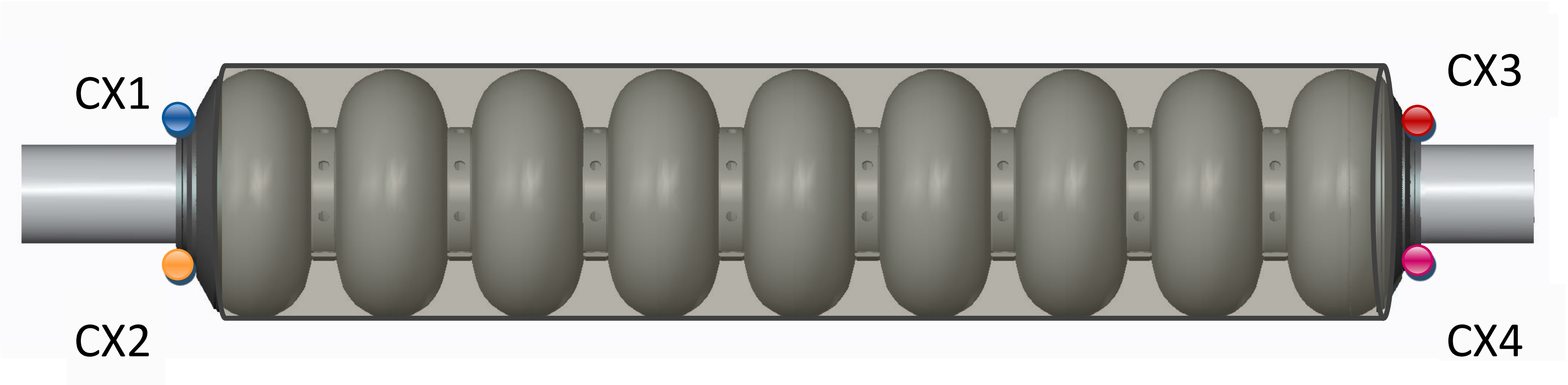


- Temperature difference at the start of the phase transition:

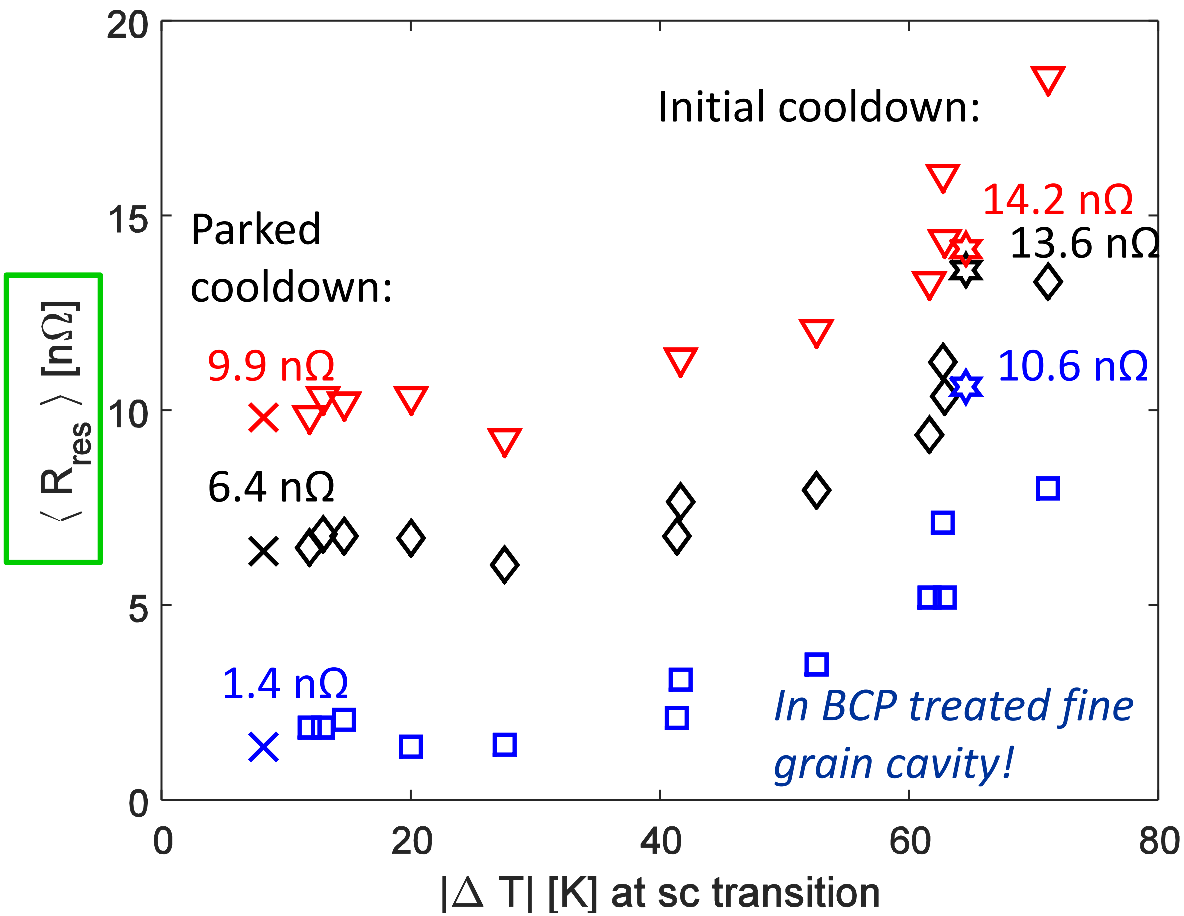
$$\Delta T = \left| \frac{T_{Cx1} + T_{Cx2}}{2} - \frac{T_{Cx3} + T_{Cx4}}{2} \right|$$

when the first sensor drops below 9.2K

- Drives thermoelectric current trough the system

1. More detailed study of the impact of **temperature difference** on the **surface resistance**

$$R_S(T) = A \cdot \exp\left(\frac{-B}{T}\right) + R_{res}$$



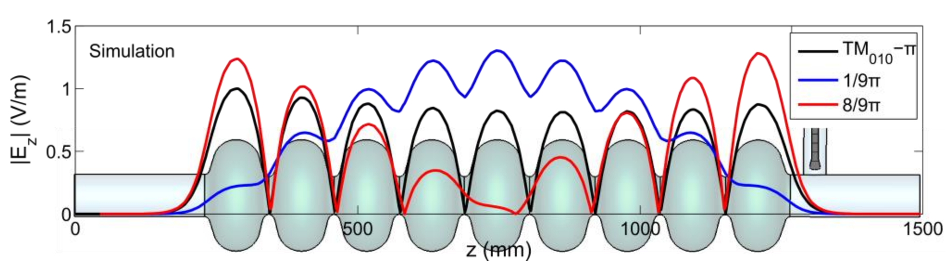
8/9 π mode

π mode

1/9 π mode

A smaller temperature difference (10 - 30K) reduces the RF losses significantly.

Even when cooled down from room temperature, low residual resistance is achievable when the cavity is parked above T_c for several hours (here 48h).



Mark: all modes are mirror symmetric

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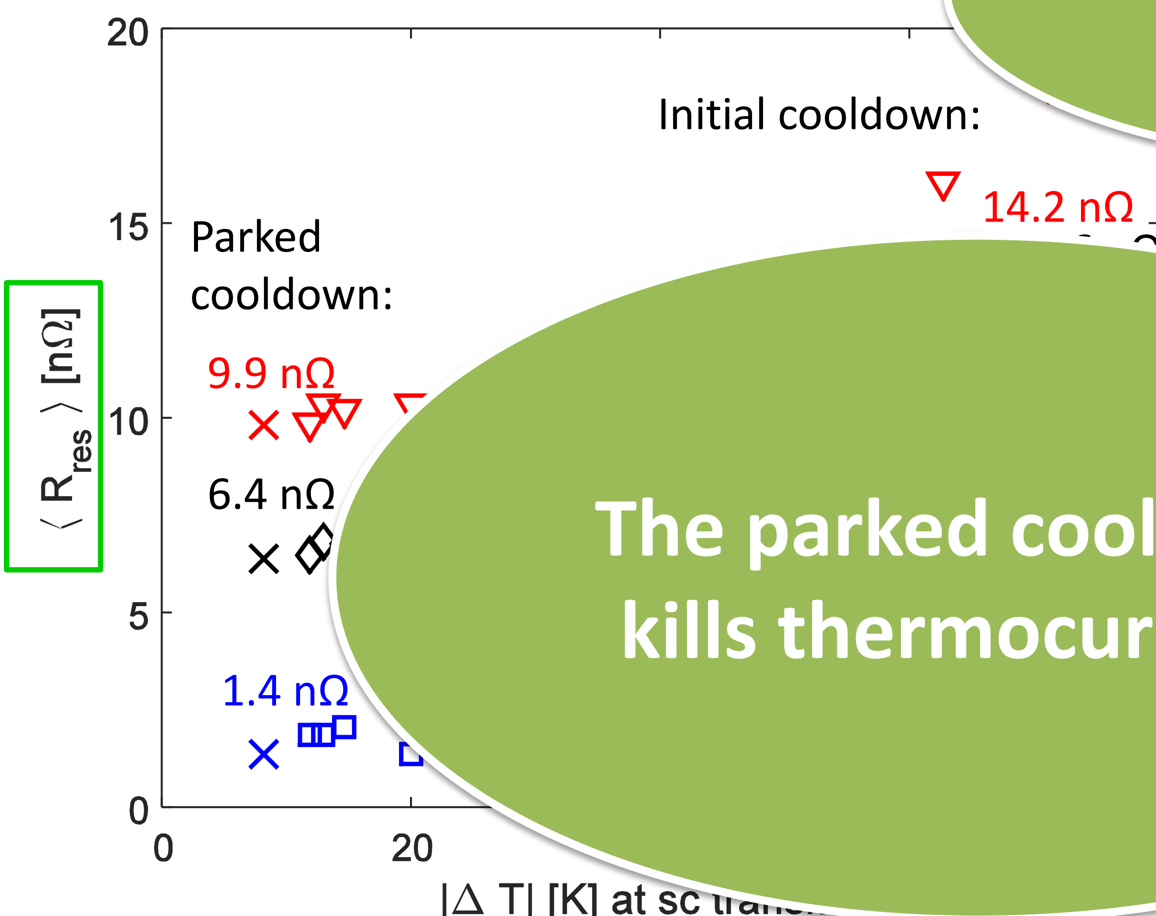

See poster MOPB017

The parked cooldown kills thermocurrents

π mode

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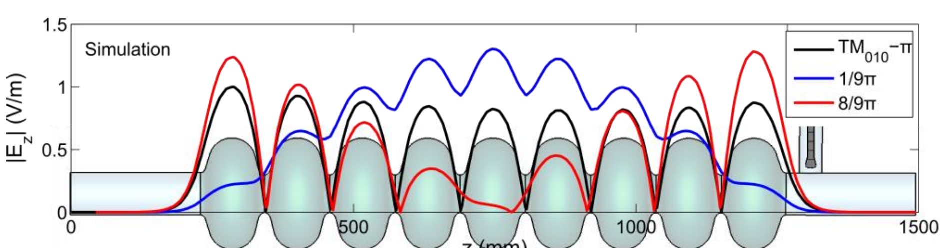

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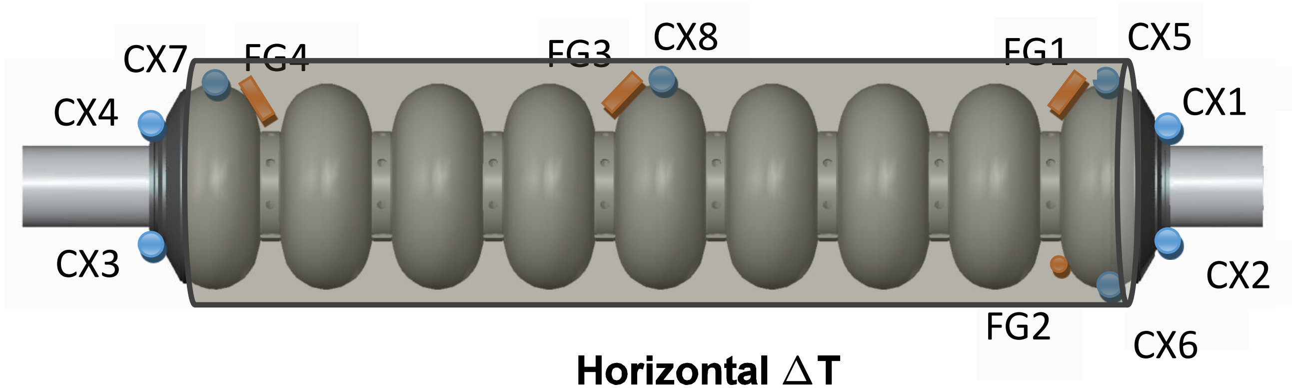
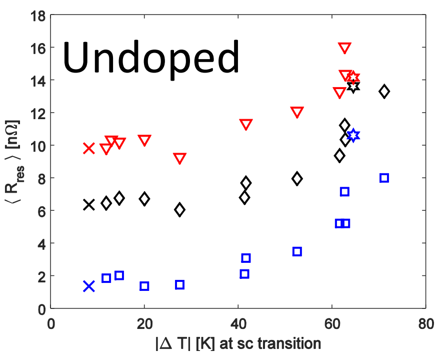
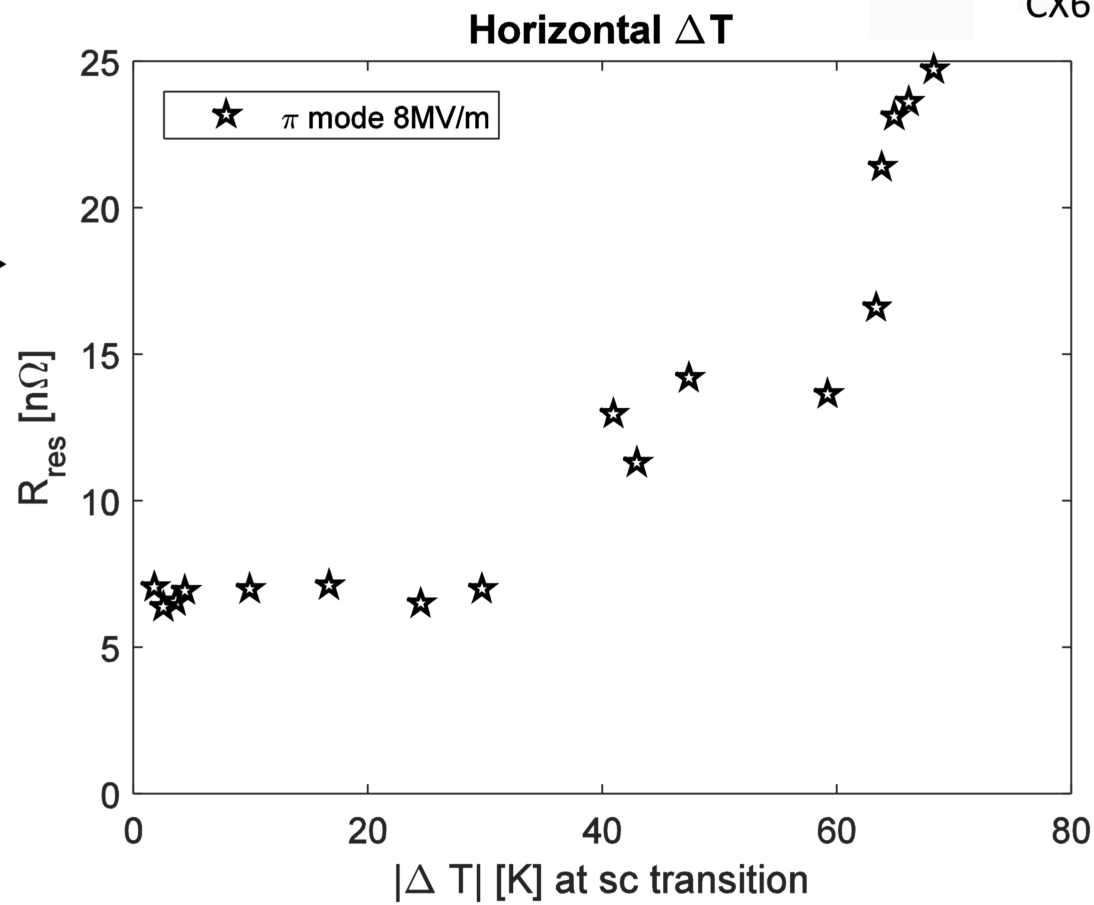
Additional question: How does it apply to a doped cavity?

Doped cavity at Fermilab:
60min N doping
with 10µm final EP







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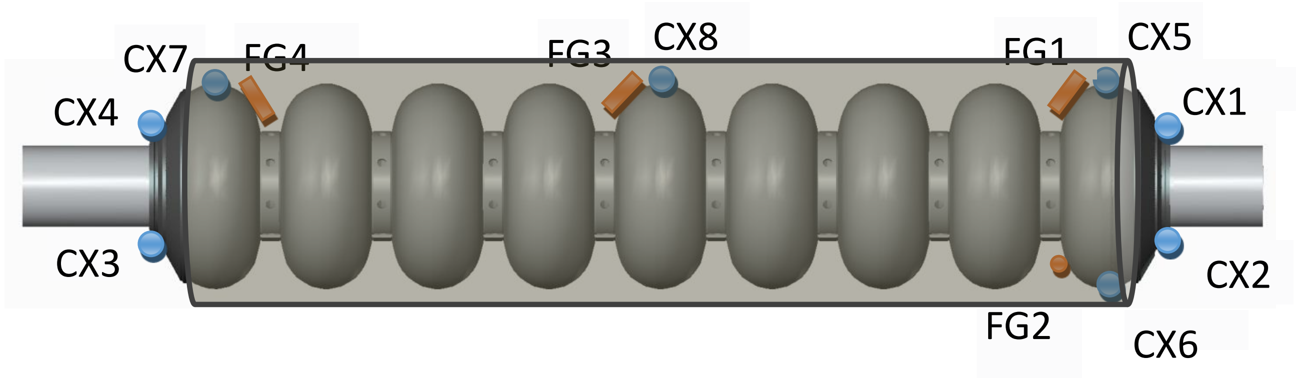

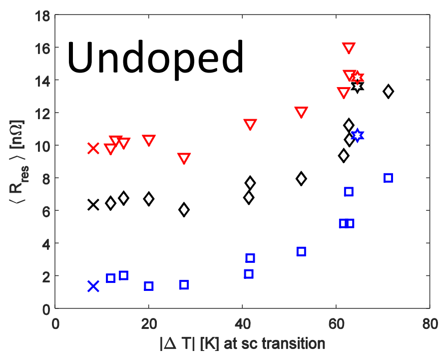

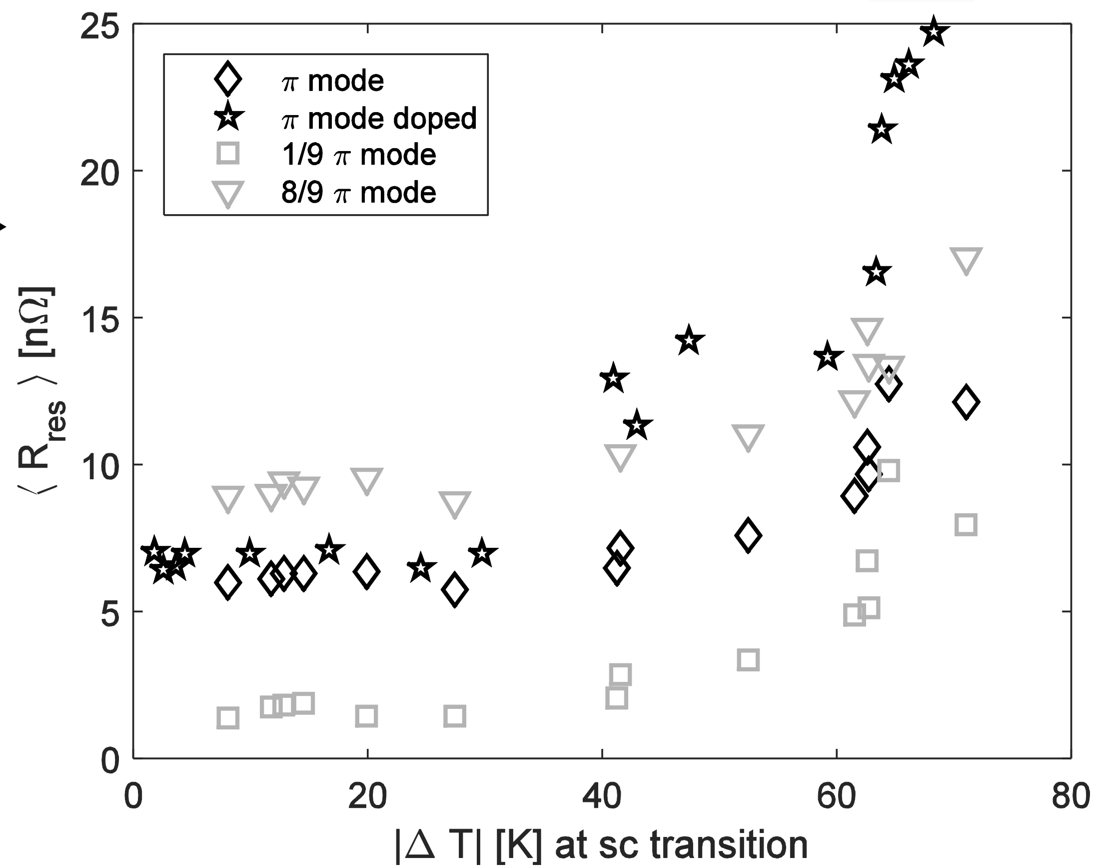

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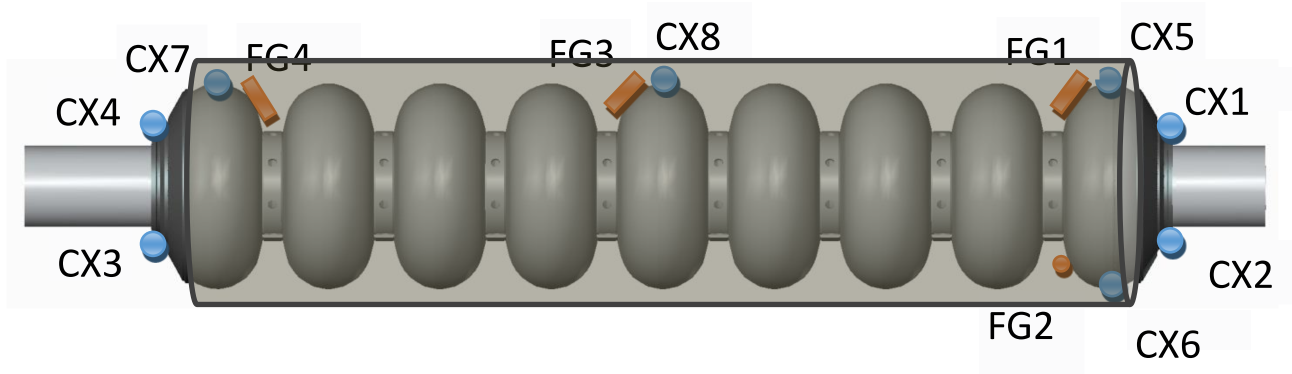
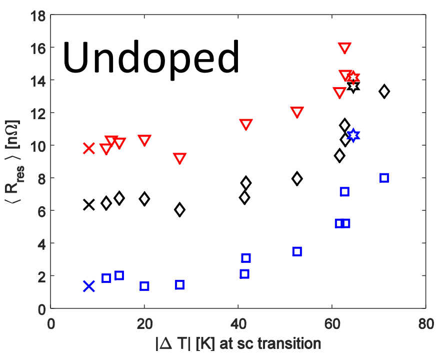
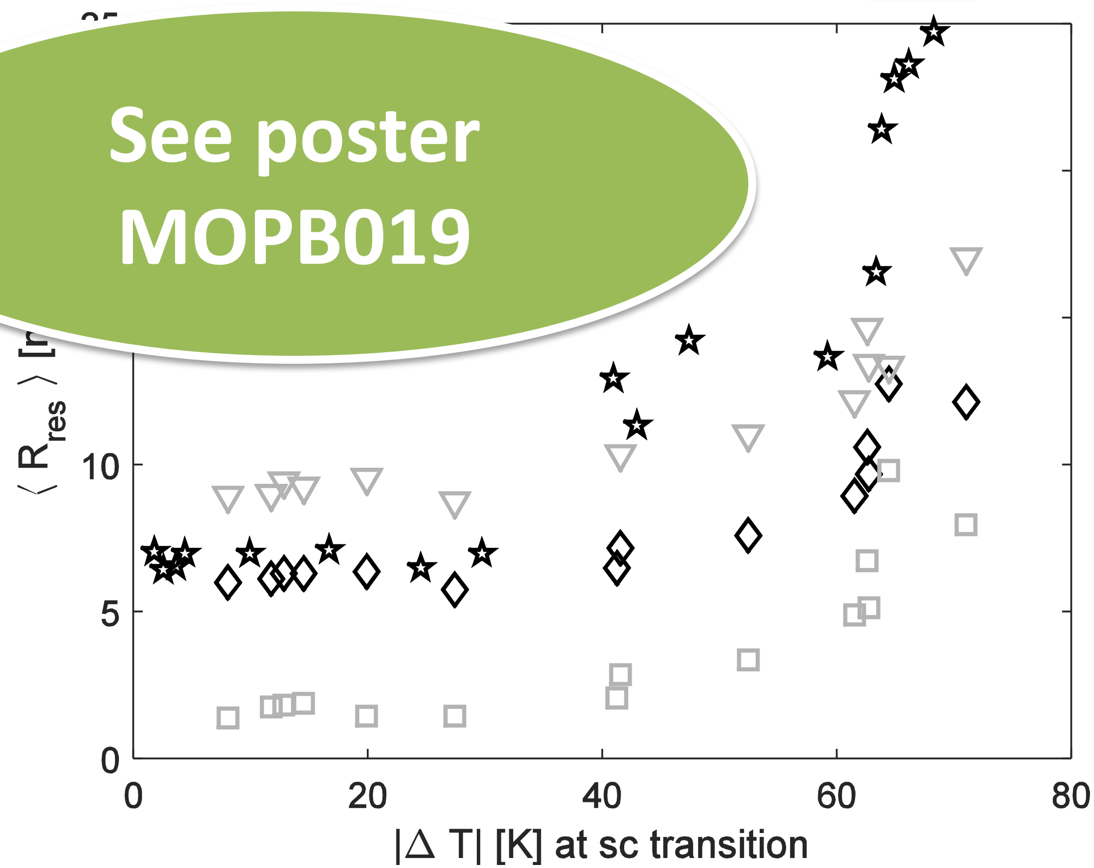
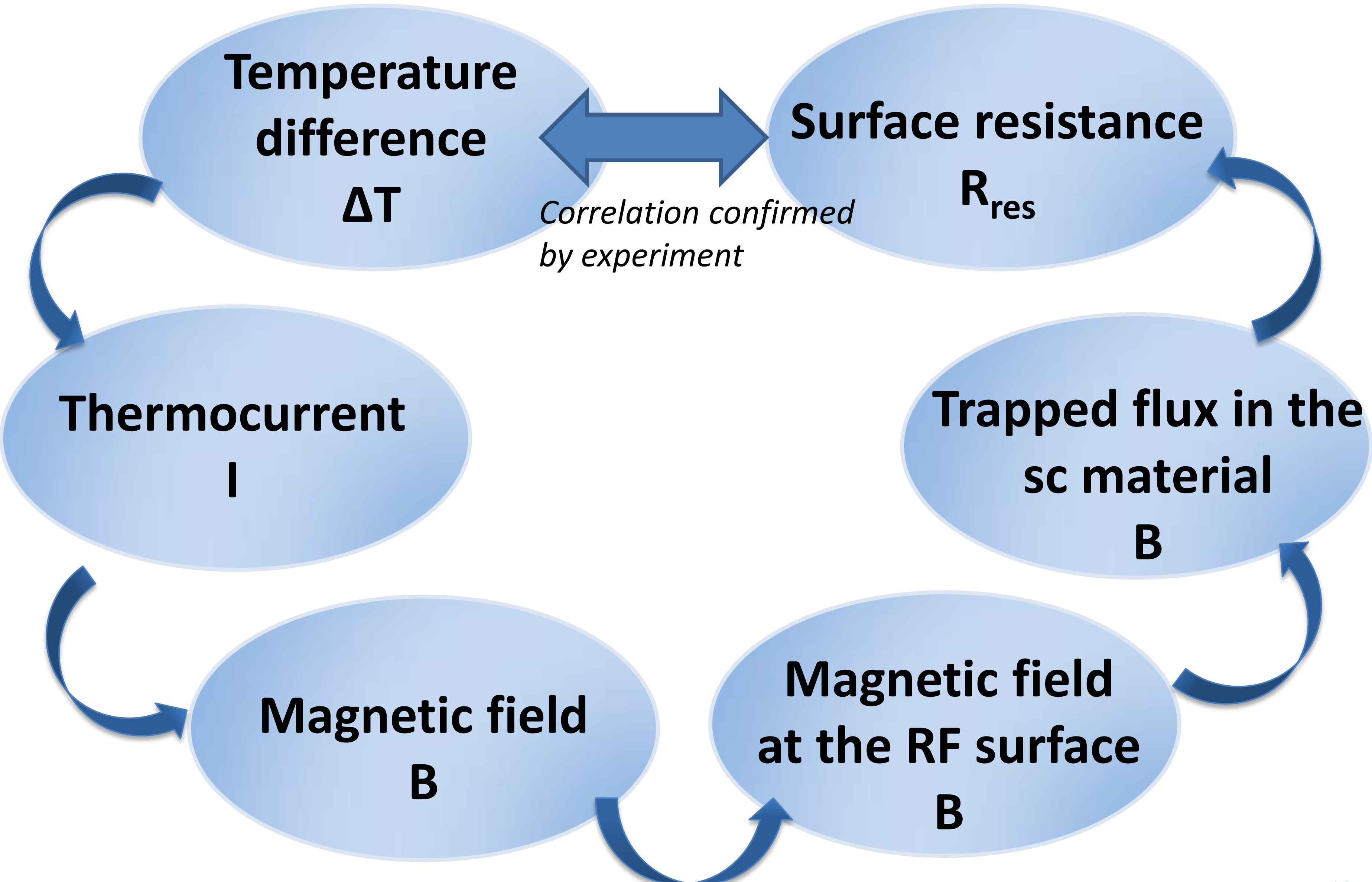






See poster MOPB019

How can we validate the thermocurrent hypothesis?



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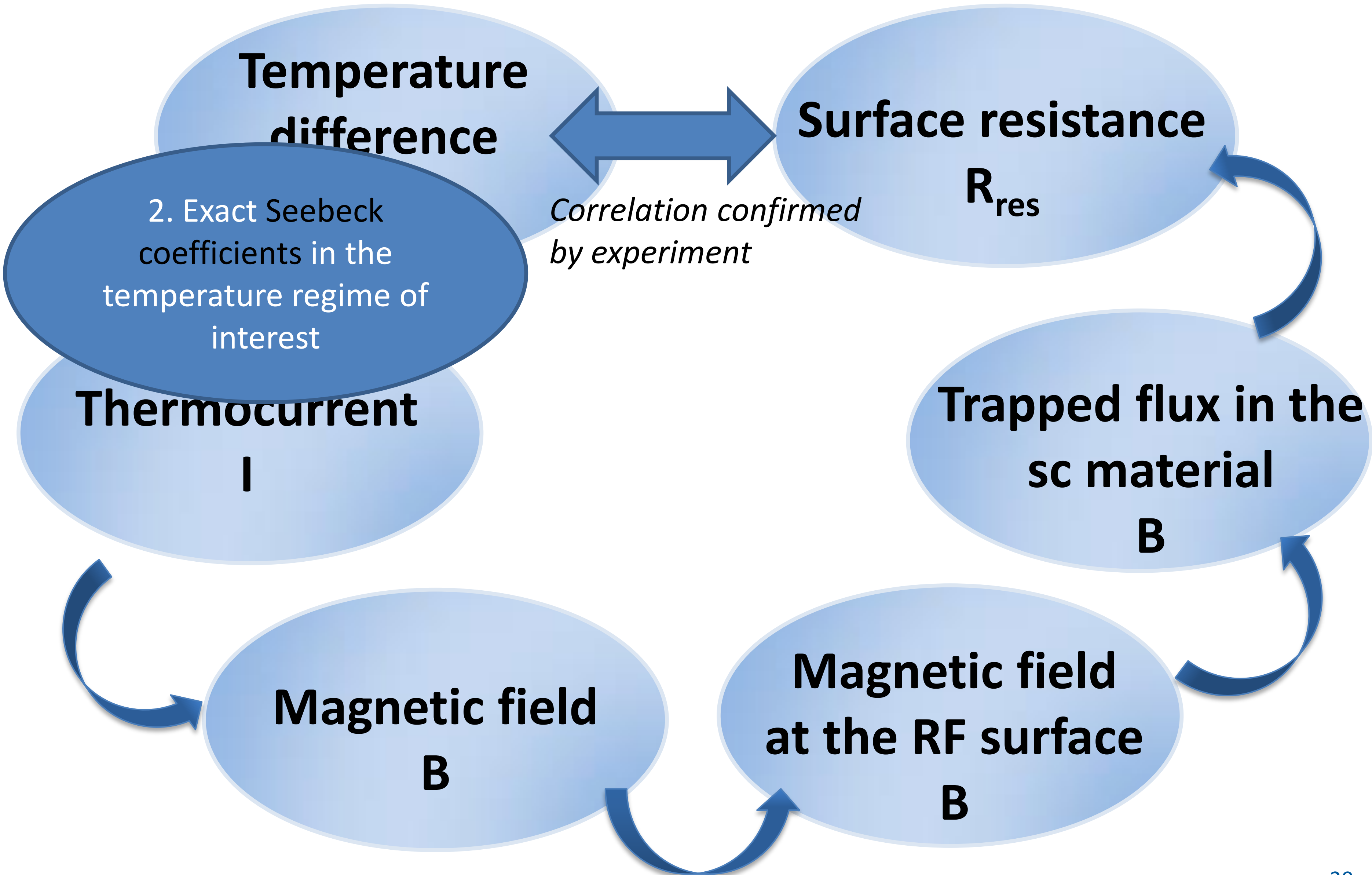
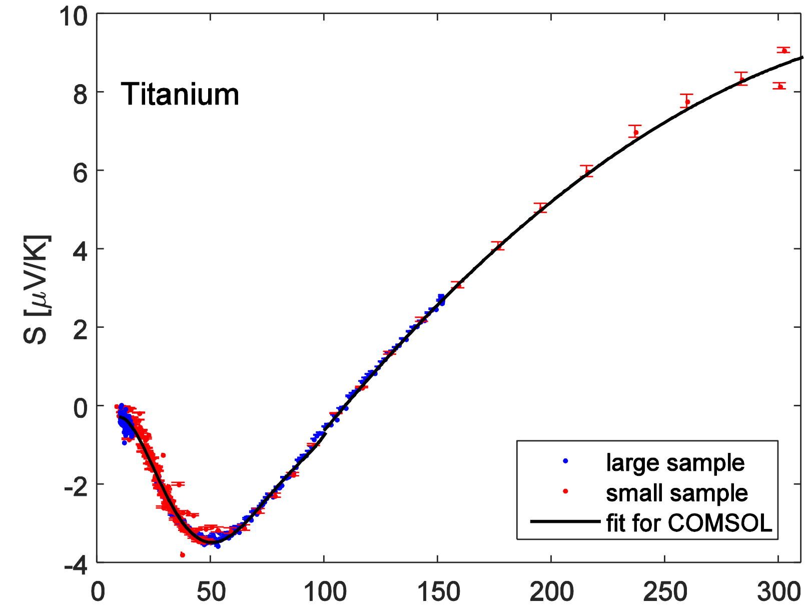
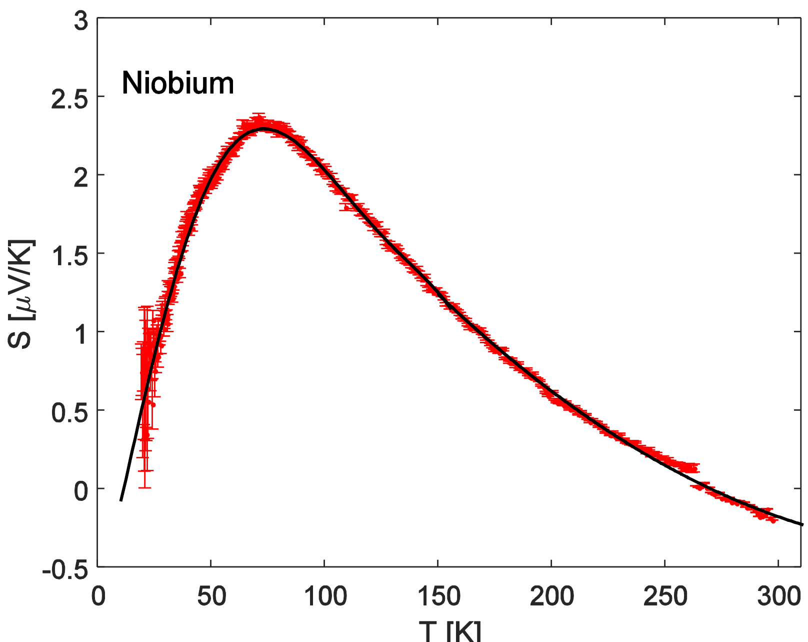


2. Exact Seebeck coefficients in the temperature regime of interest





Samples from material as used in cavity fabrication:

- Niobium (RRR = 300)
- Titanium (grade 2)

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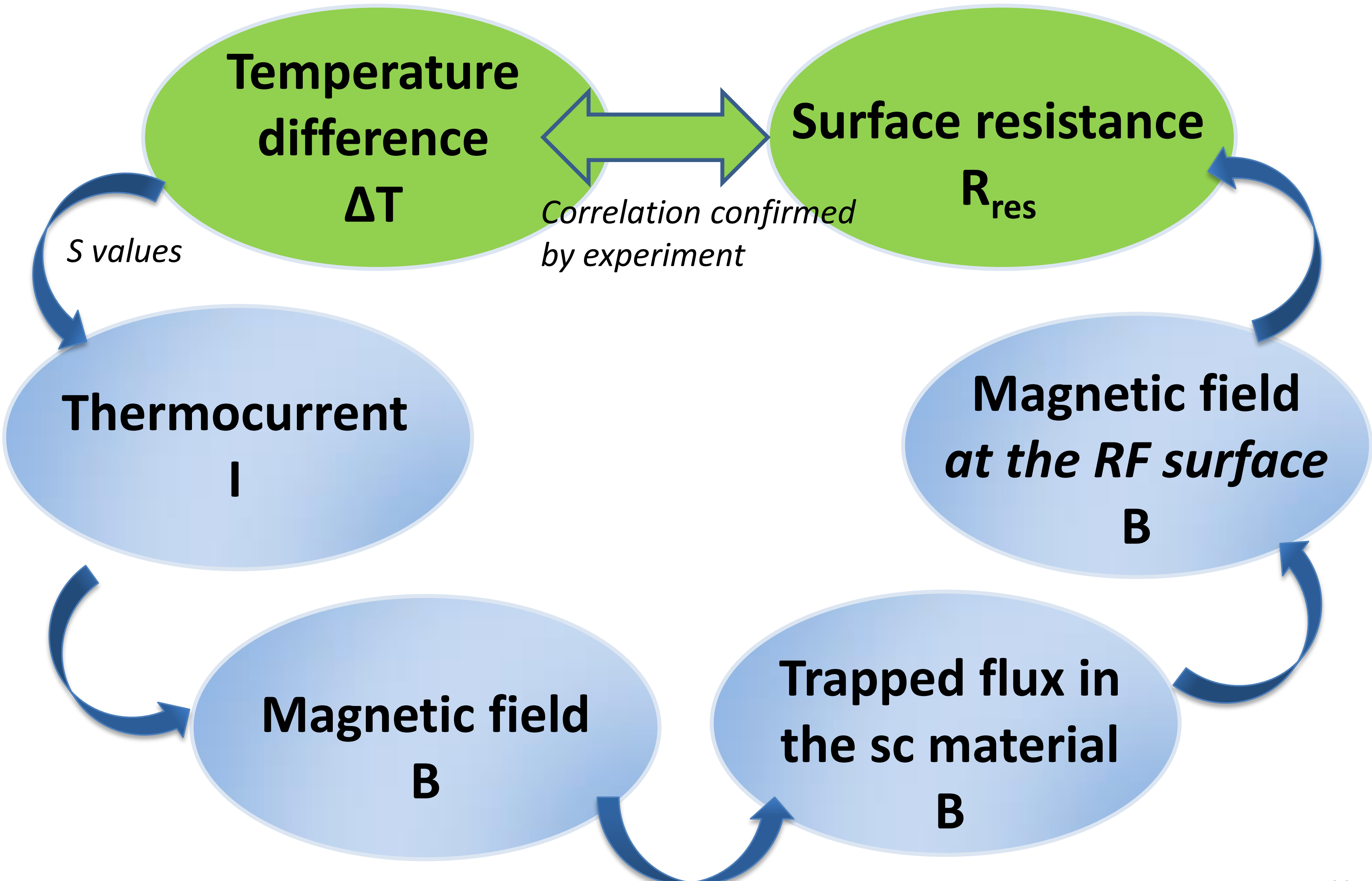

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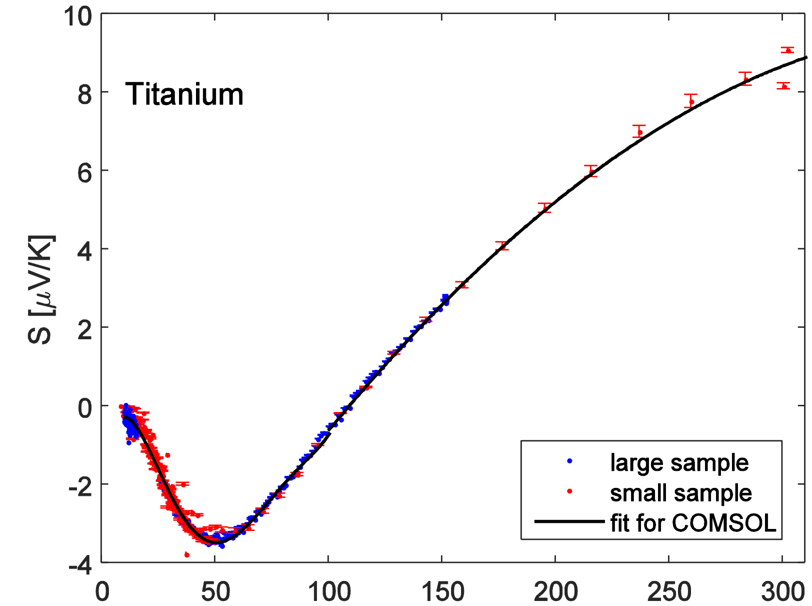

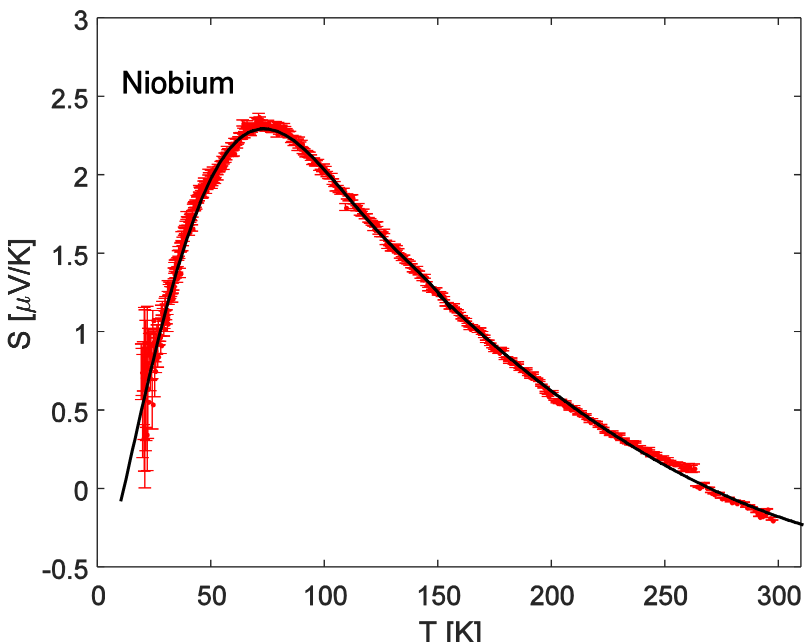

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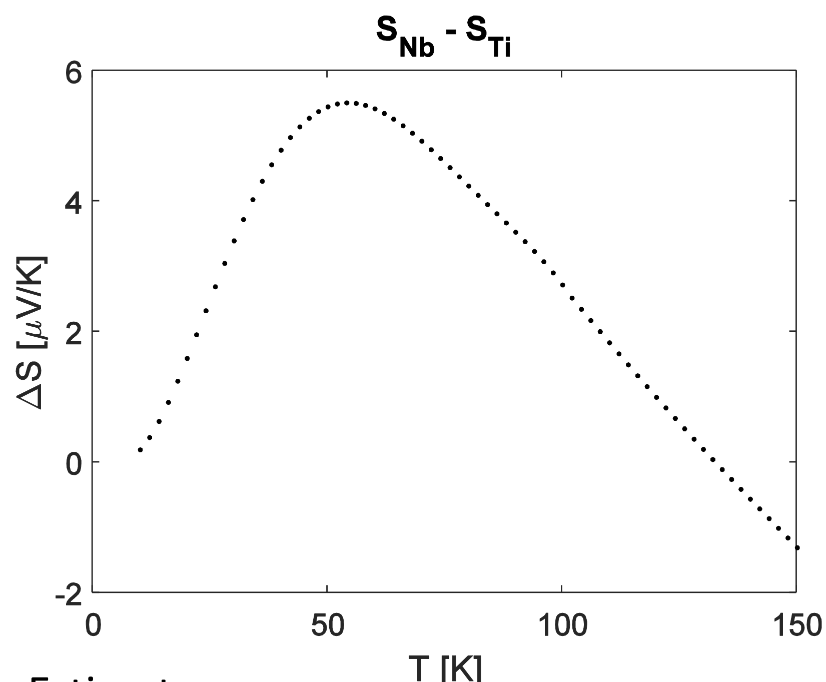
ΔS has maximum beween 50K and 100K



Estimate:

I = Δ S · ΔT / R = 1 μV/K · 100 K / 100 μΩ = 1 A

10cm distance of a 1 A line current: 2μT

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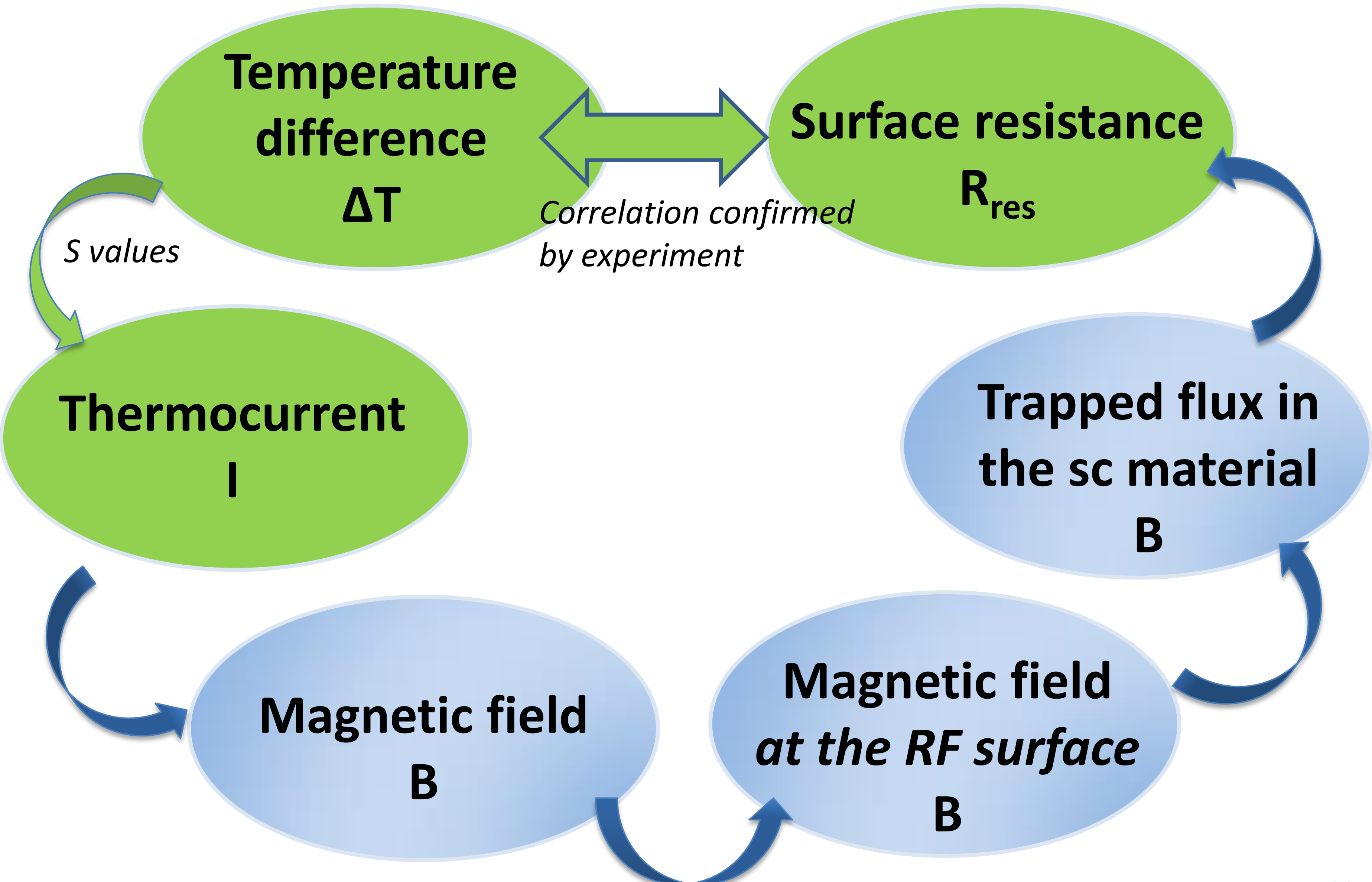
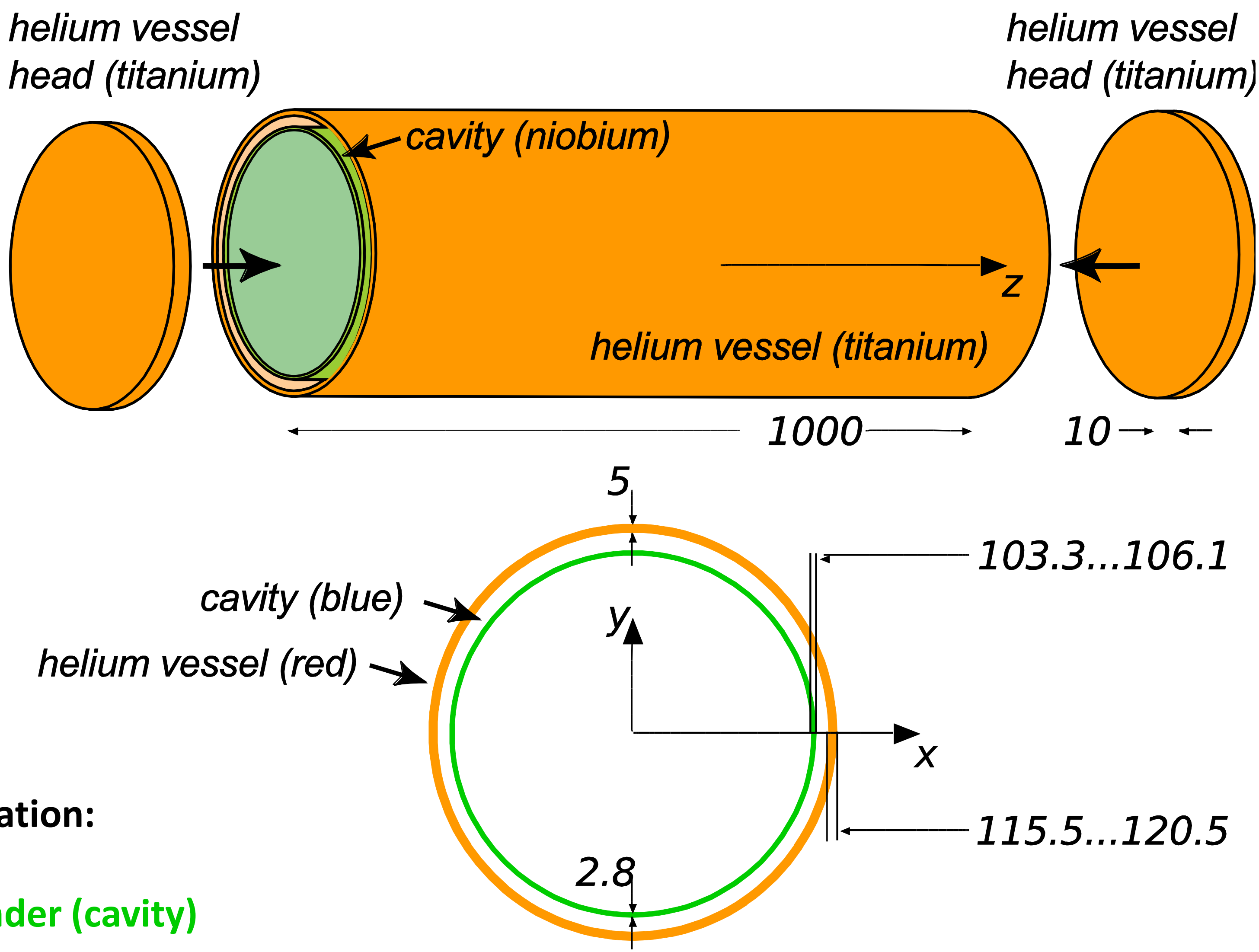


3. Geometry of thermocurrents



COMSOL simulation:

- **Niobium:**
  Inner cylinder (cavity)
- **Titanium:**
  Outer cylinder (He vessel)
  End plates (vessel head)

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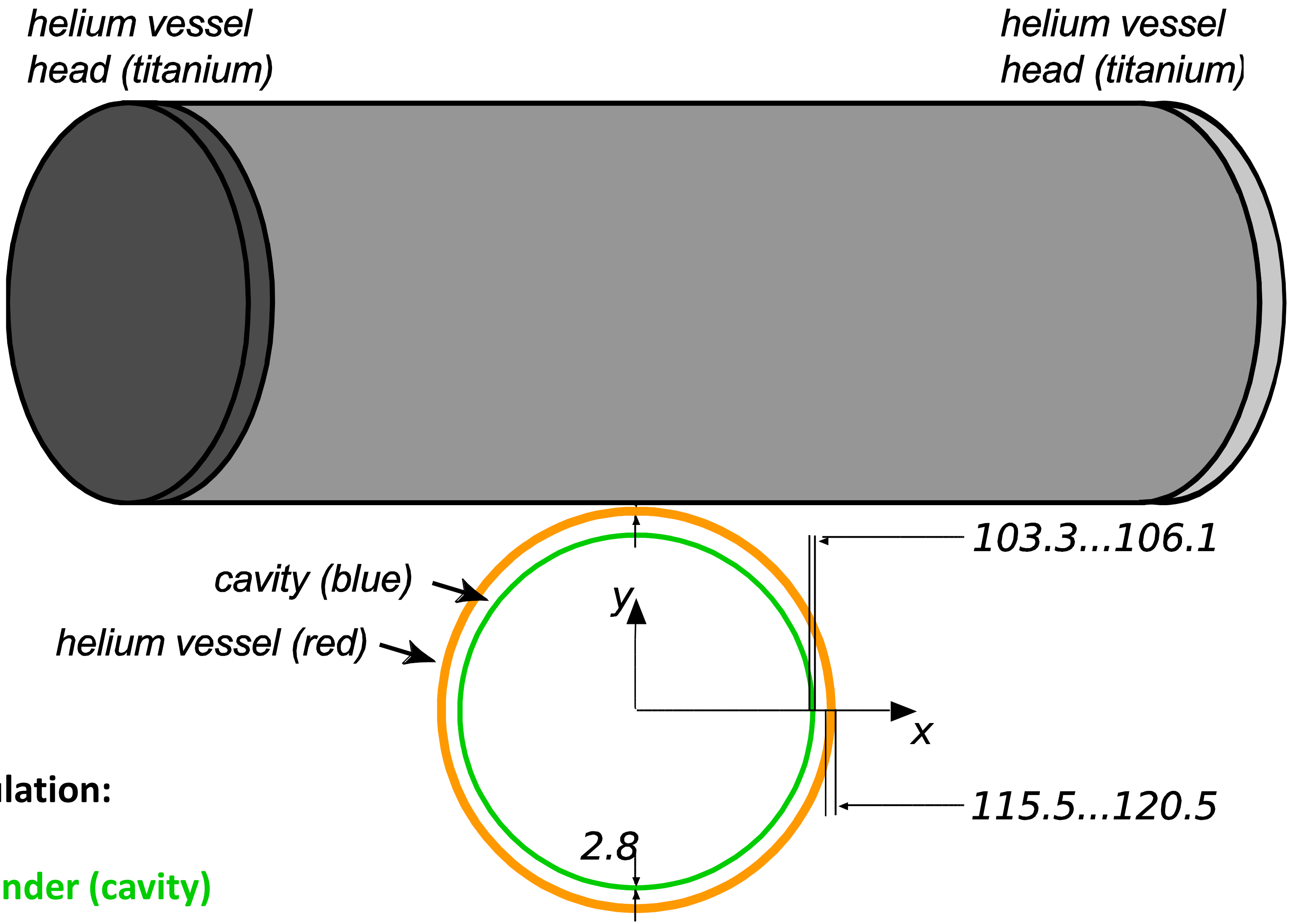

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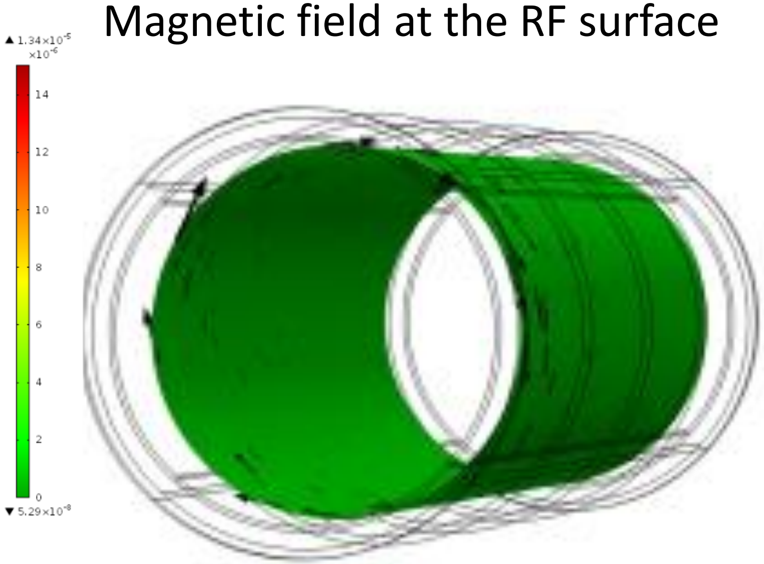
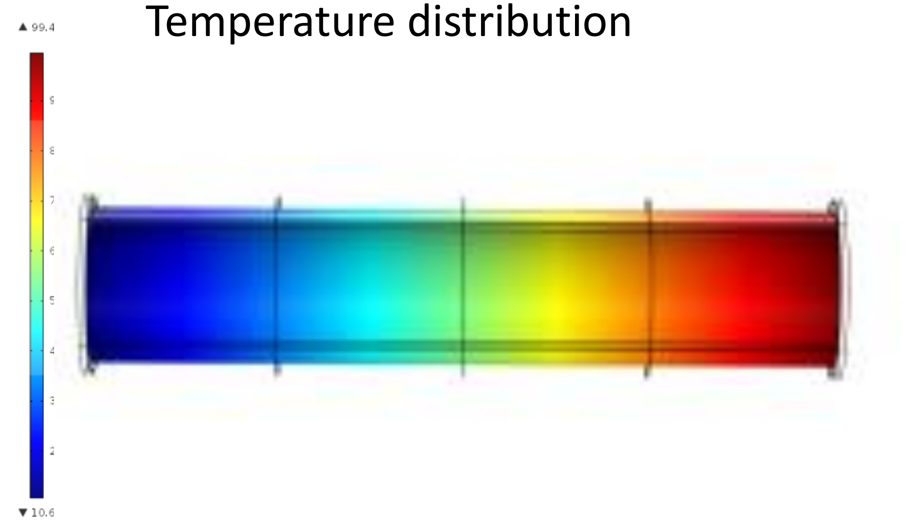
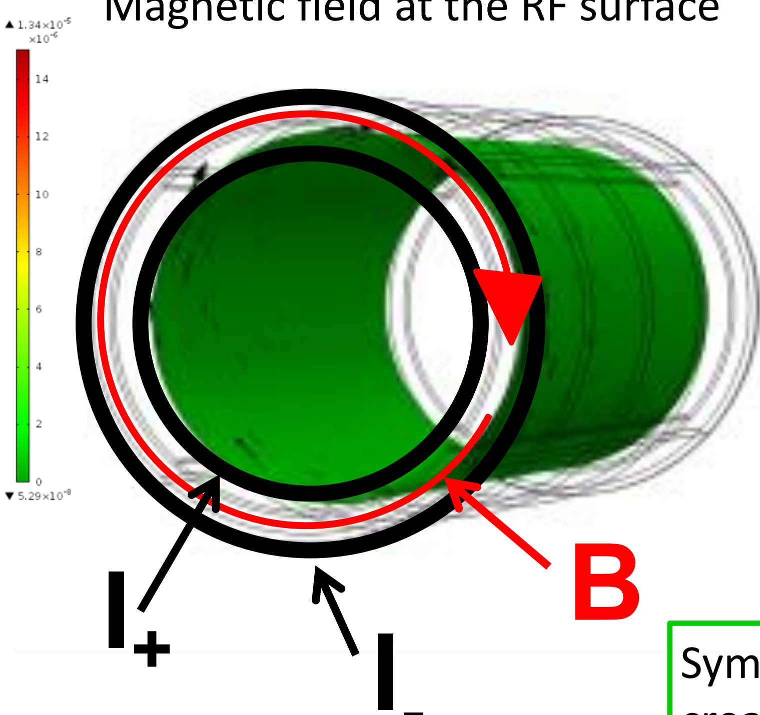




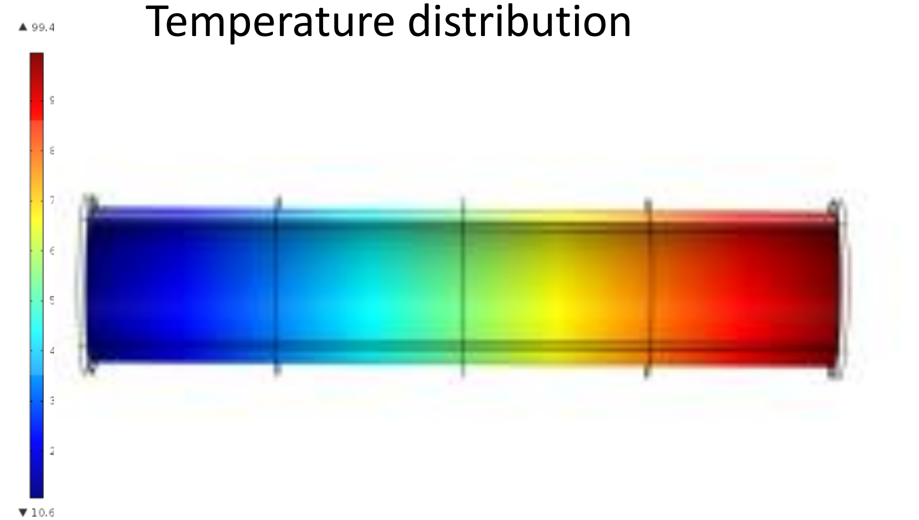
Symmetric current configuration creates no field on the RF surface.

3. Geometry of thermocurrents

Magnetic field at the RF surface



Temperature distribution



Symmetric current configuration creates no field on the RF surface.

3. Geometry of thermocurrents: Breaking the symmetry

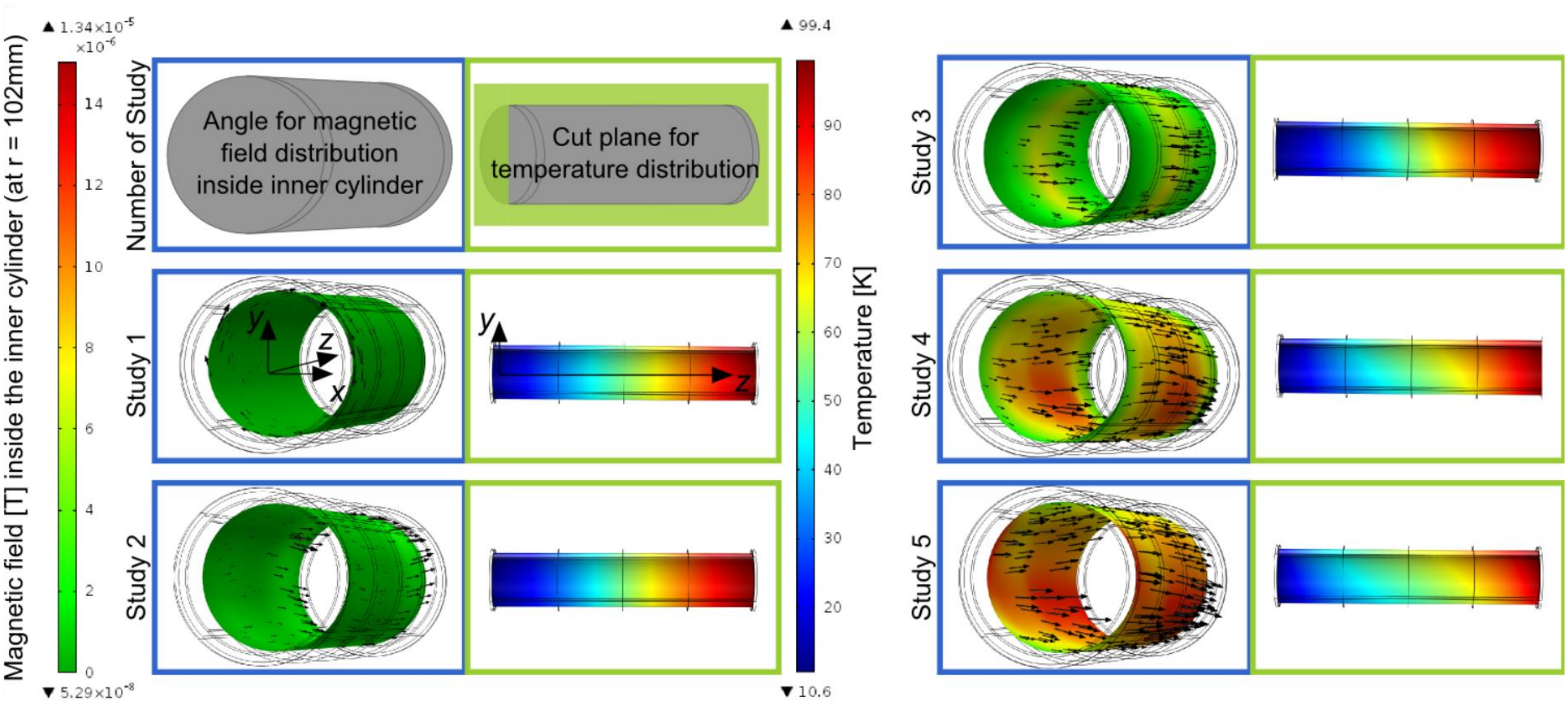
Symmetry can be broken by:

- Mechanical errors: *A. Crawford, "A Study of Thermocurrent Induced Magnetic Fields in ILC Cavities", http://arxiv.org/abs/1403.7996*

- Temperature dependance of electrical resistance:

Tank is filled from bottom to top → Additional temperature difference bottom to top

3. Geometry of thermocurrents: Additional temperature difference bottom to top



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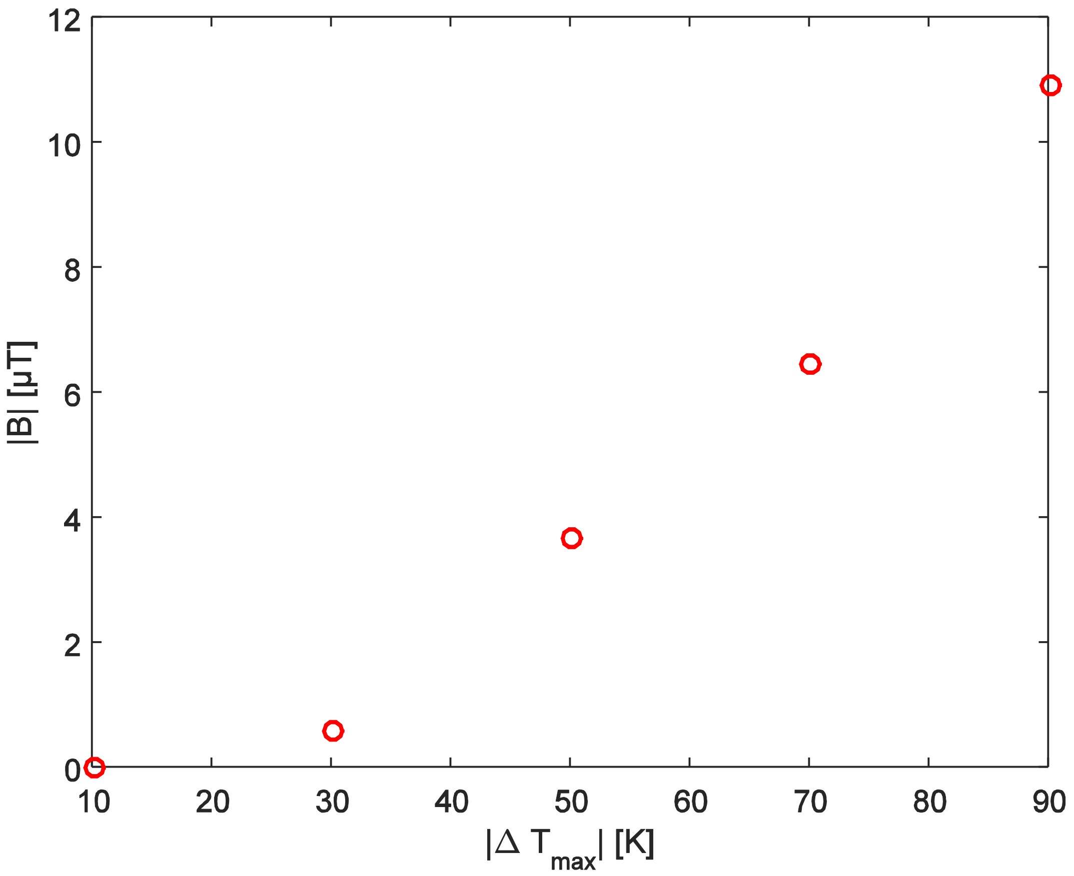
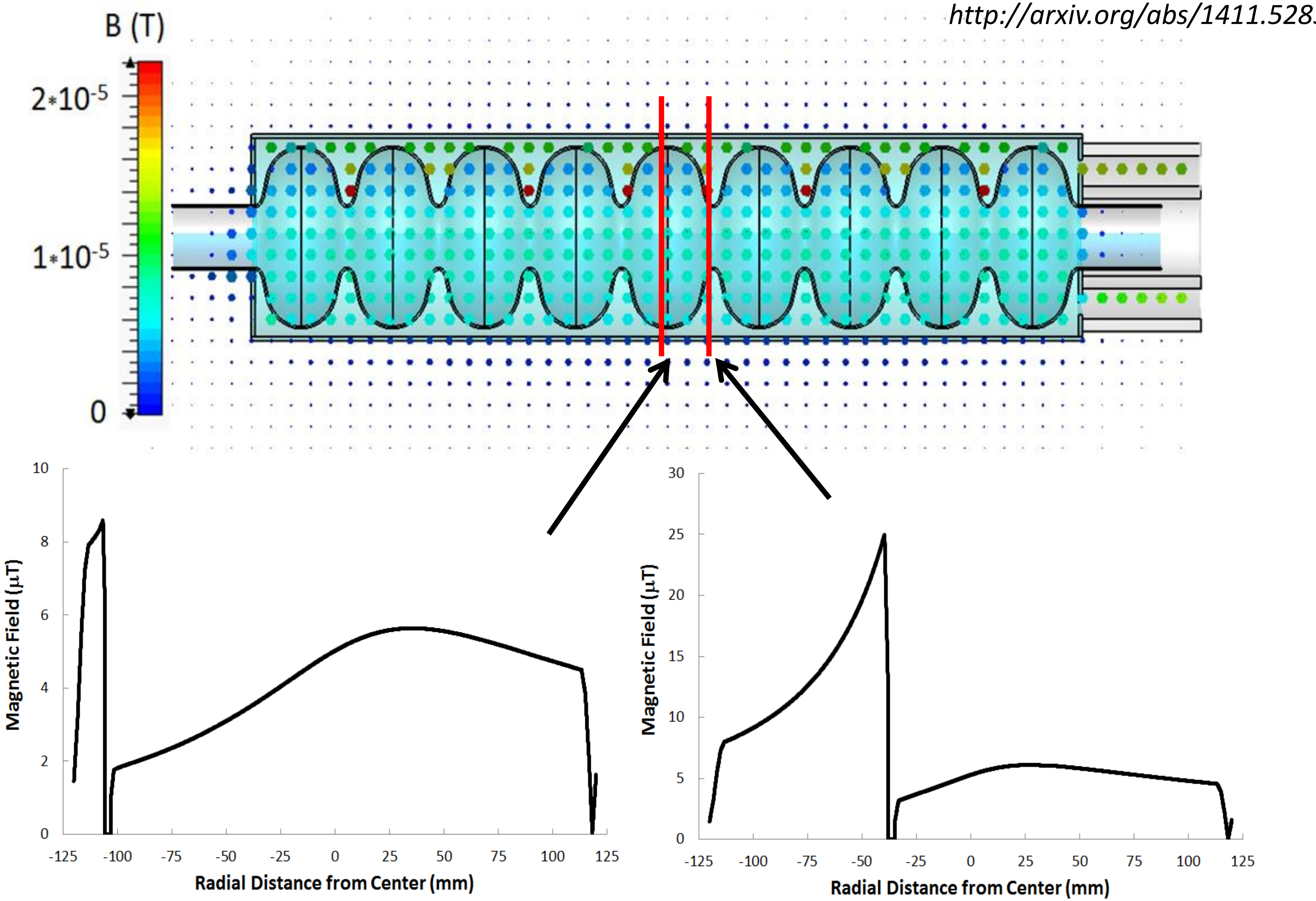


3. Geometry of thermocurrents: Highest degree of asymmetry when parts of the cavity are superconducting

Courtesy R. Eichhorn

R. Eichhorn et al., "Thermocurrents and their Role in high Q Cavity Performance", http://arxiv.org/abs/1411.5285



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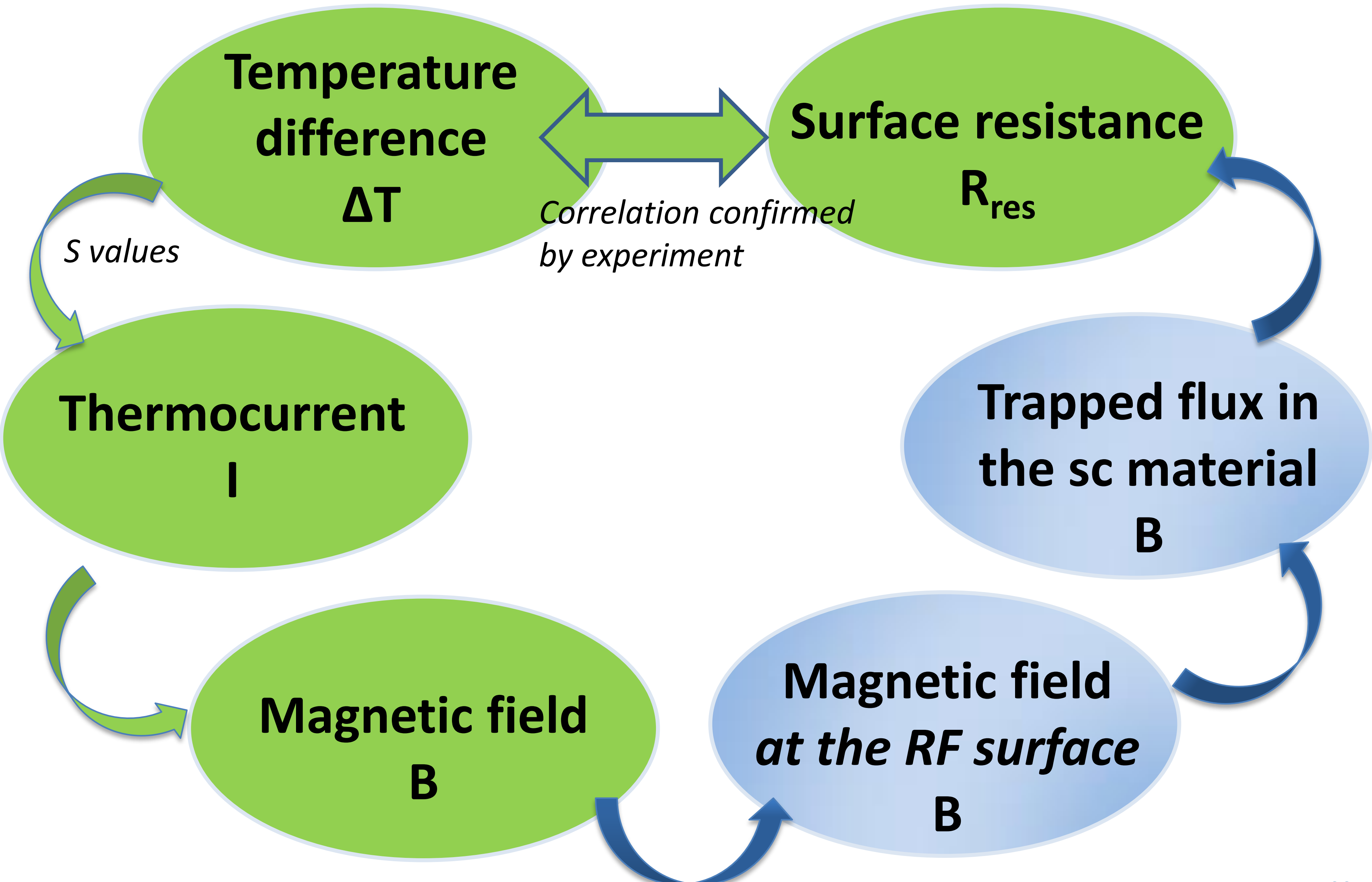
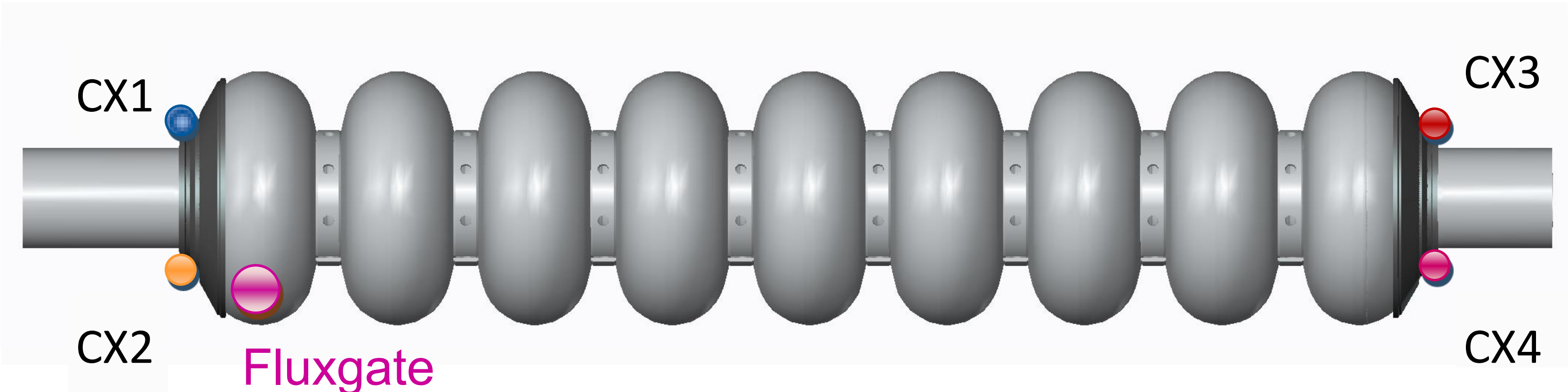
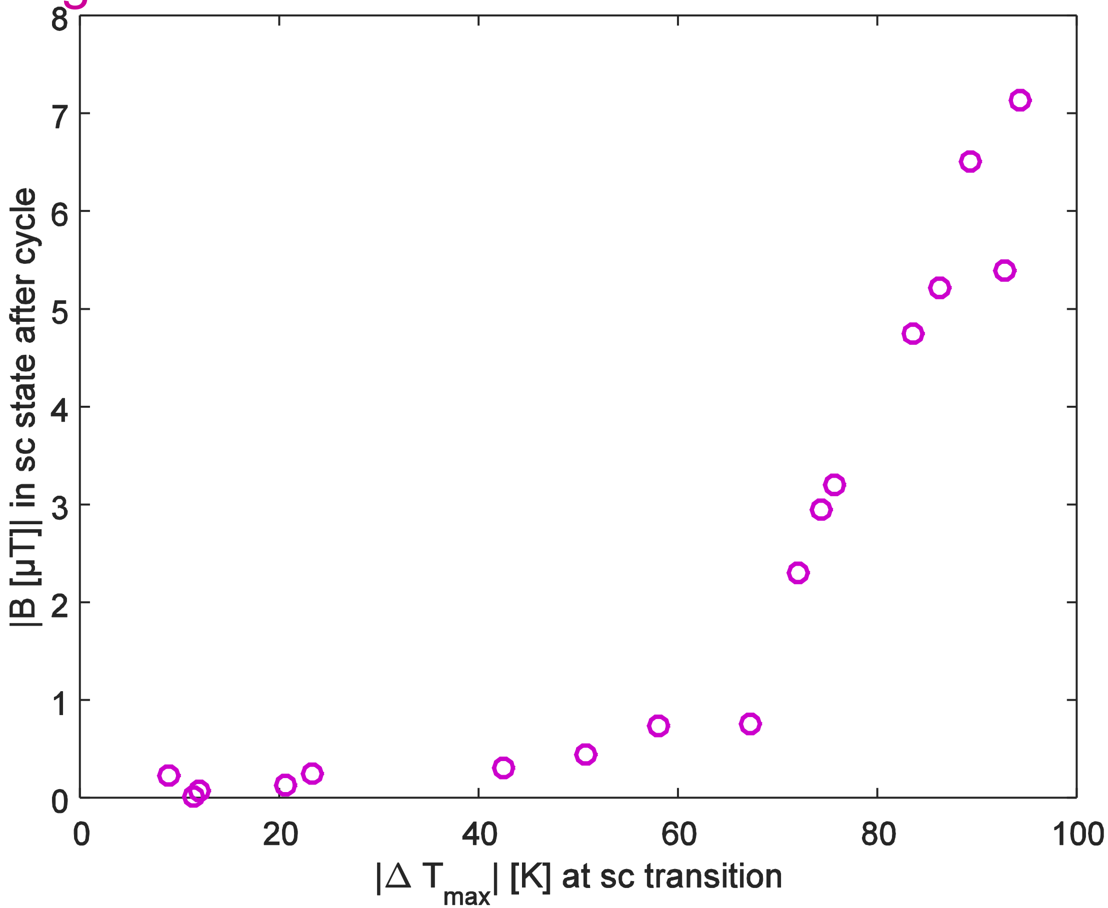


4. Direct measurement of the magnetic field on RF surface





Mark: ΔT is not mean but maximum value

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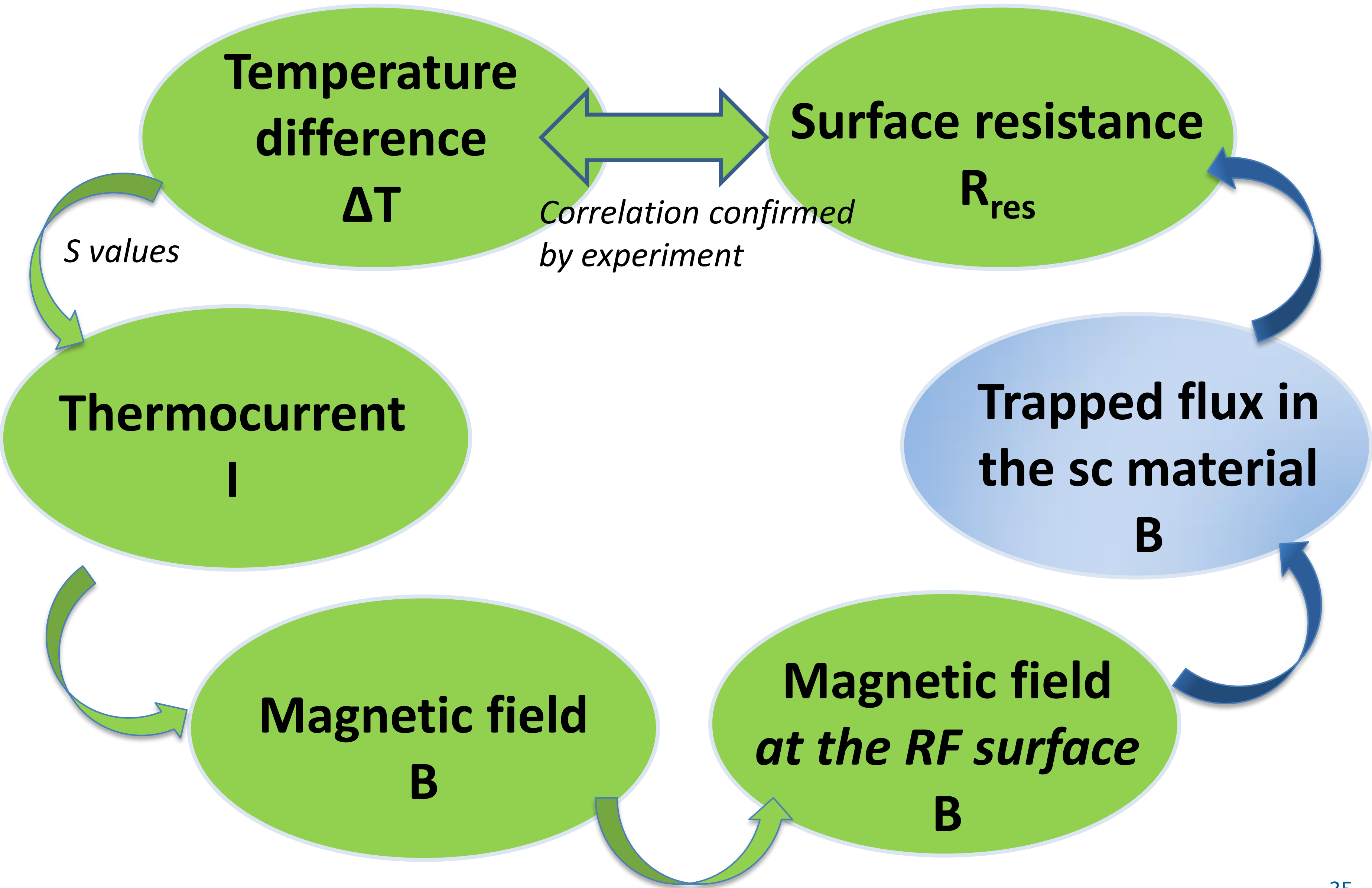
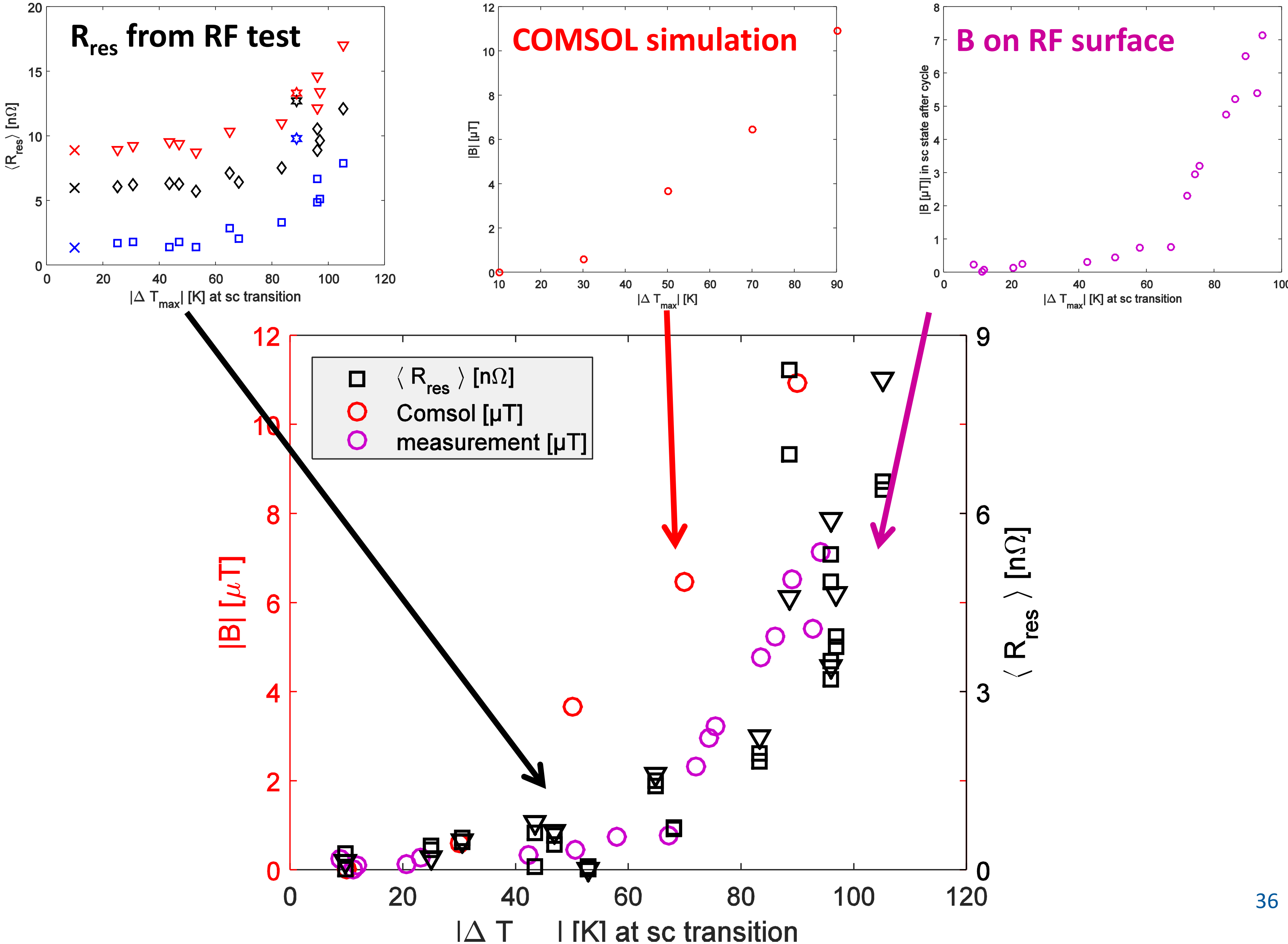


Summary: Thermocurrents in horizontal cavity test



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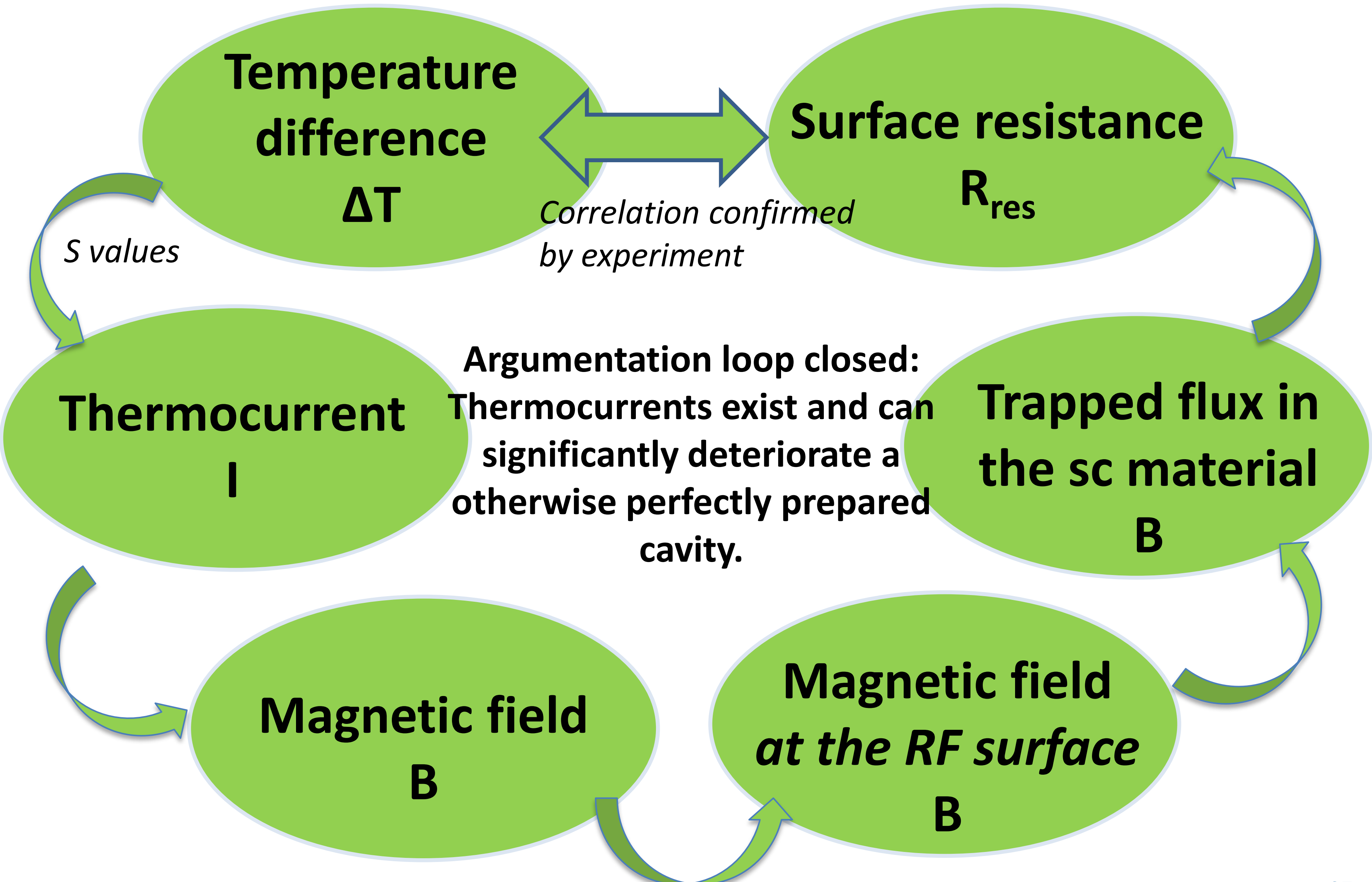
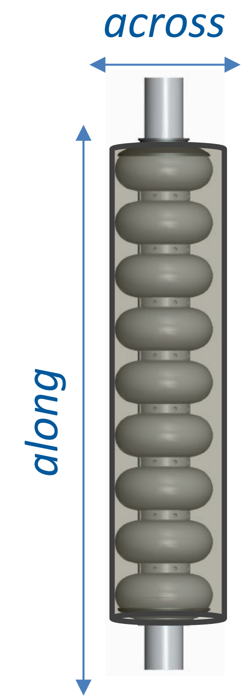


Does the effect apply to every setup?



Not, if…
… only one aspect is satisfied

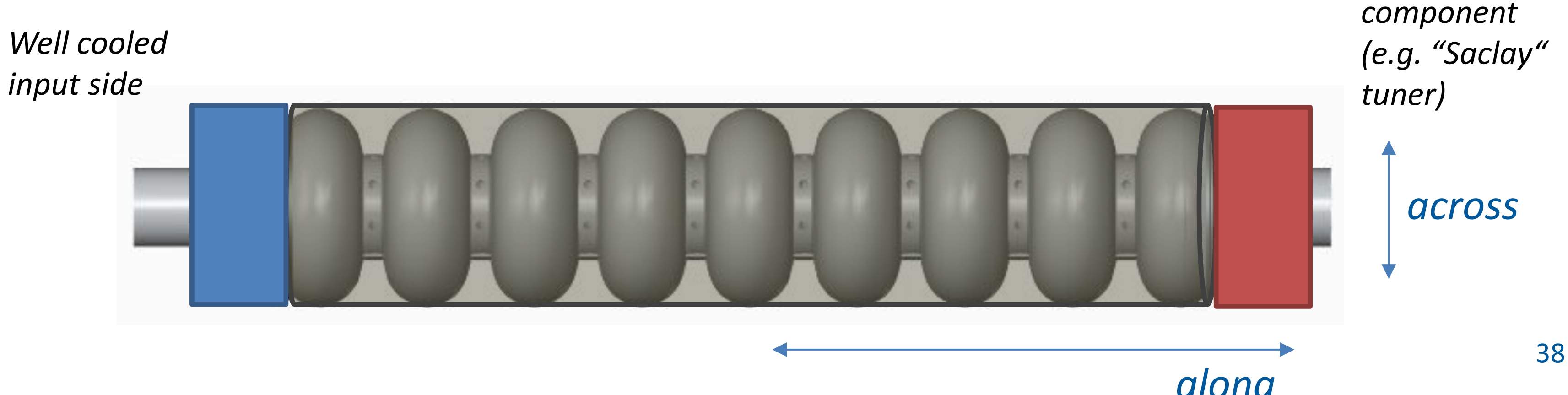
… There is no LHe tank (undressed vertical test)
→ *no closed circuit*

… The system is (electrically) symmetric (vertical test)
→ *no gradient across cavity*

… The system allows for symmetric LHe fill (modified LHe tank)
→ *no gradient along cavity*

Yes, if…
… both aspects are satisfied

… especially with couplers and tuners!



Thank you for your attention!

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