RF Characterization of Superconducting Samples

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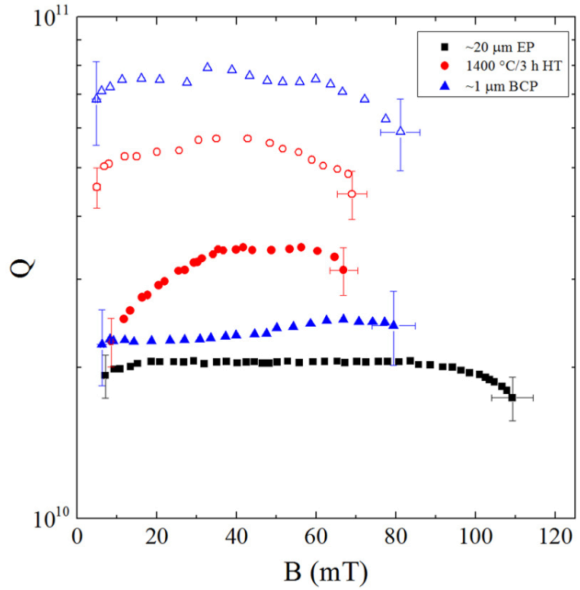
HZB Helmholtz Zentrum Berlin

Detailed understanding of cavity loss mechanisms

- Bulk Niobium
  surface treatments, N-doping/infusion
- Thin films
  Nb/Cu, Nb_3Sn, Multilayer, …

[G. Ciovati et. al., APL 104, 092601]



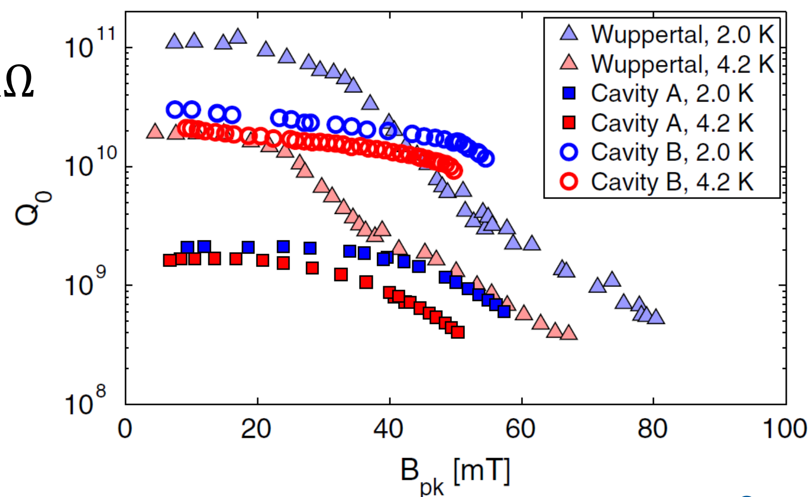
How does an ideal tool look?
(without going through the hassle of building an entire cavity)

→ Measure RF surface resistance
- $\omega,\ B_{RF},\ T$
- High resolution: $Q_0 \approx 3 \cdot 10^{11} \leftrightarrow R_S \approx 1\ \mathrm{n\Omega}$

→ Characterize SC properties
- RF penetration depth, B_c, m.f.p.
- Flux trapping, cooling conditions

→ Small samples, easy to change

[S. Posen, M. Liepe, PRSTAB 17, 112001]



Characterization Test Facility implemented at HZB

- October 2015: Milestone 78 fulfilled
- PhD thesis of Raphael Kleindienst
- Successful commissioning runs
- Sample development

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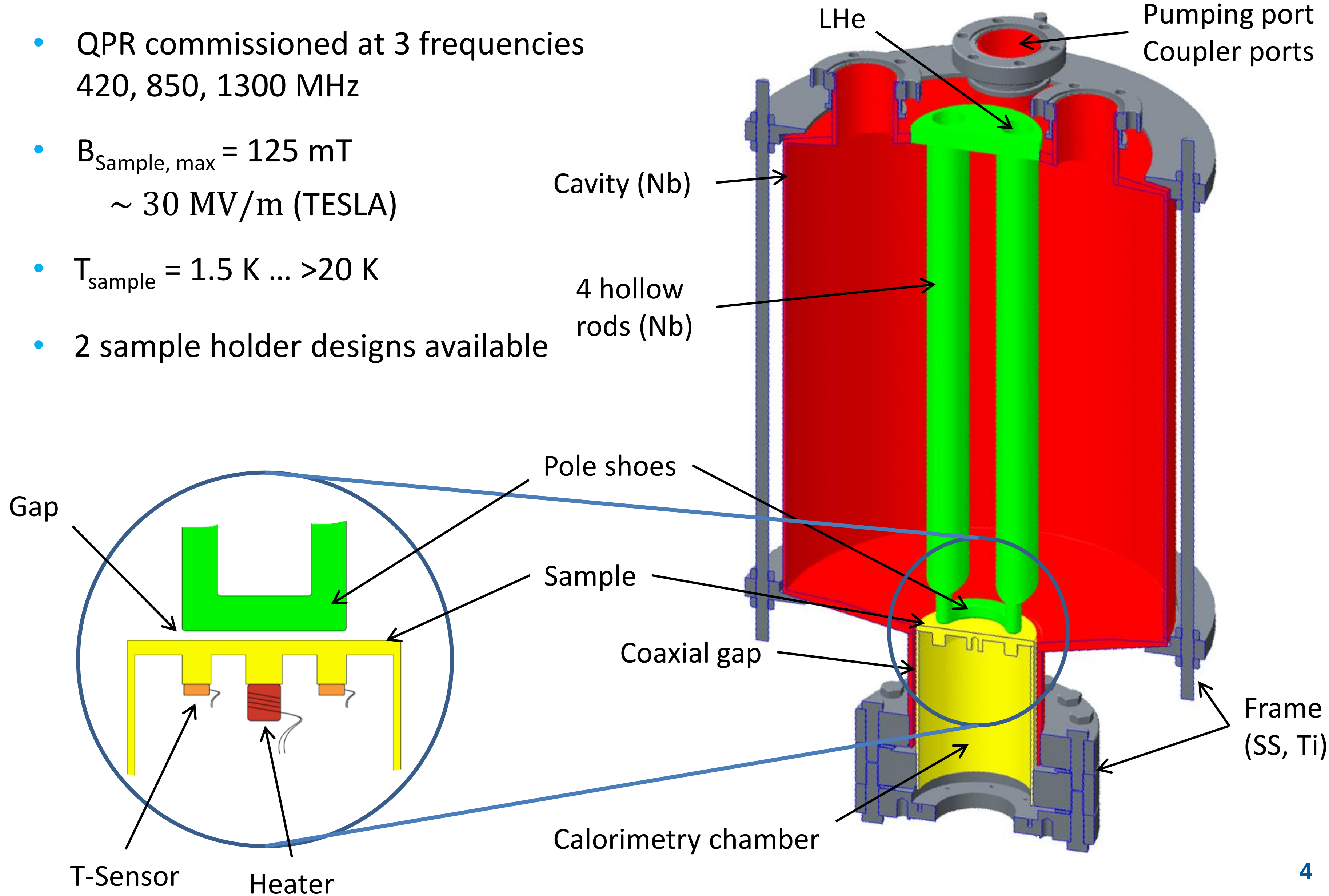
- This talk: Further characterization methods
  - Trapped magnetic flux
  - Penetration depth
  - RF critical field

→ to be continued in the framework of ARIES

The Quadrupole Resonator (QPR)

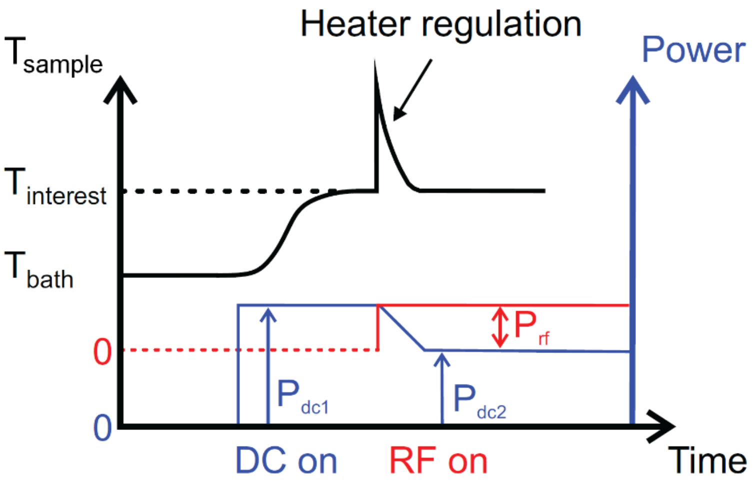
- QPR commissioned at 3 frequencies 420, 850, 1300 MHz
- $B_{Sample, max}$ = 125 mT
  $\sim 30\ \mathrm{MV/m}$ (TESLA)
- T_{sample} = 1.5 K … >20 K
- 2 sample holder designs available



Resolution & measurement limits

$$P_{\mathrm{RF,\,diss}} = \frac{1}{2}\iint_{sample} R_S \left|\vec{H}\right|^2 dS = R_S \frac{\omega U}{G} = P_{\mathrm{DC,1}} - P_{\mathrm{DC,2}}$$

$$\Rightarrow R_S = \frac{G}{\omega U}\left(P_{\mathrm{DC,1}} - P_{\mathrm{DC,2}}\right) = c(\omega) \cdot \frac{P_{\mathrm{DC,1}} - P_{\mathrm{DC,2}}}{P_{\mathrm{RF\ pickup}}}$$



- Temperature resolution: 0.1 mK (calibrated cernox sensors)
- Surface resistance limit: $\Delta P_{DC} \geq 1\ \%$ and $B_{RF} \leq 125\ \mathrm{mT}$

Sample temperature	Reference power	R_S resolution limit
1.9 K	2.4 mW	0.006 nΩ
2 K	4.6 mW	0.011 nΩ
4 K	83 mW	0.2 nΩ
7 K	375 mW	0.9 nΩ

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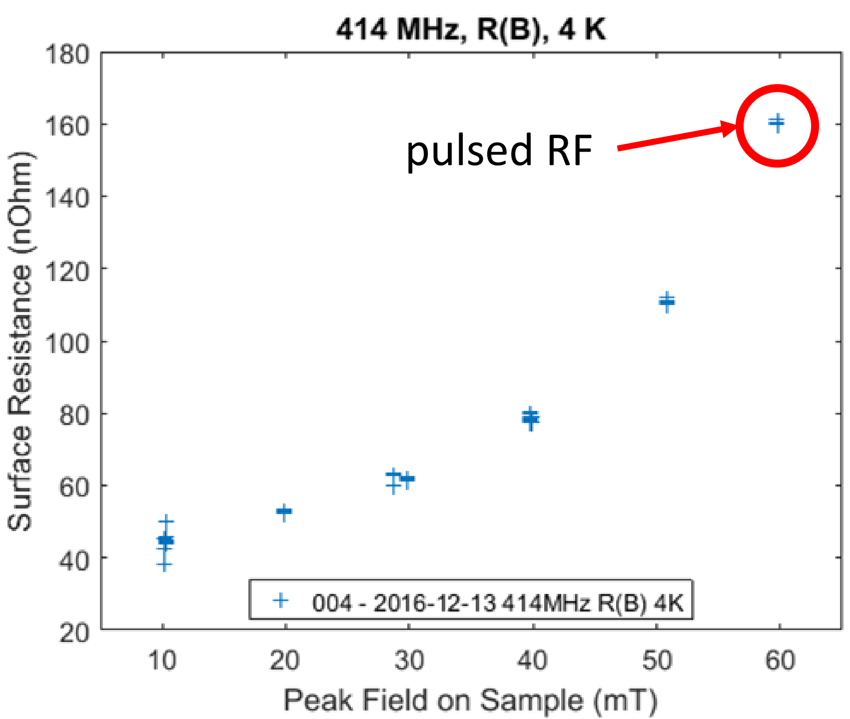
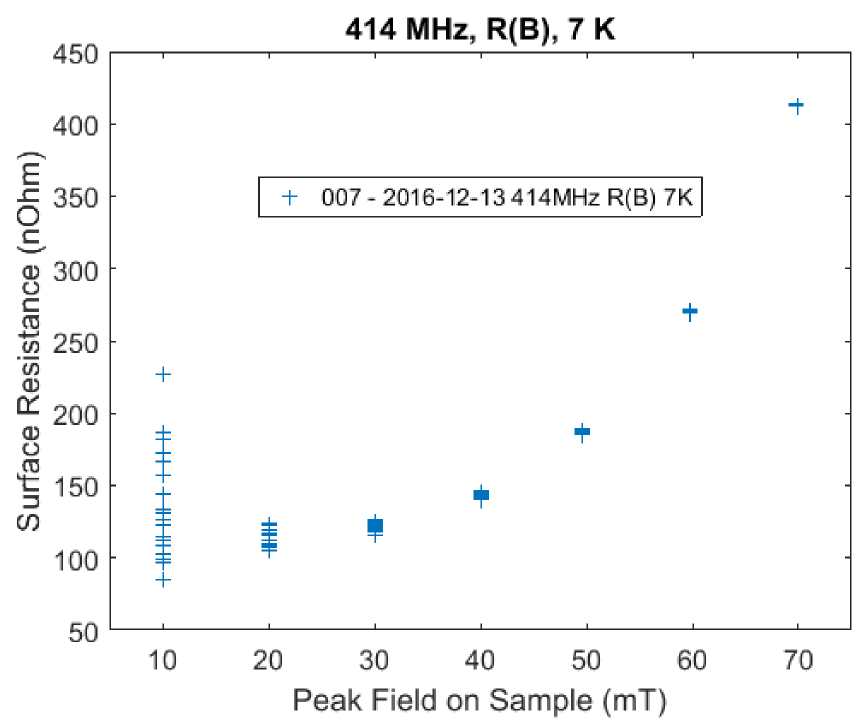
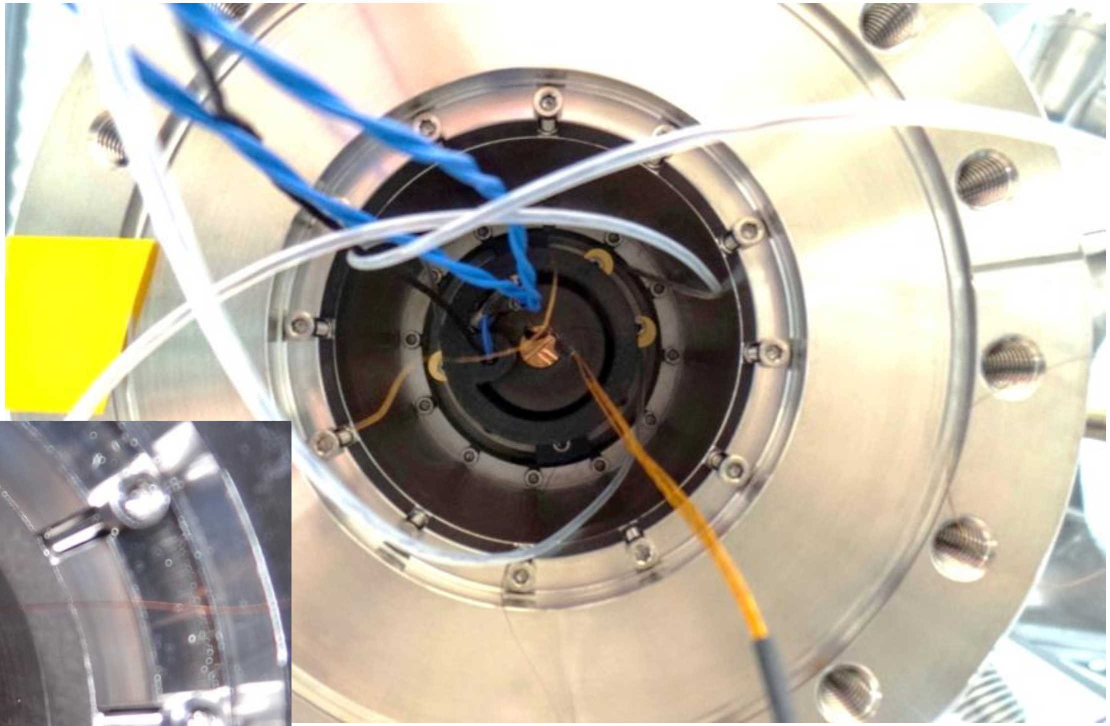
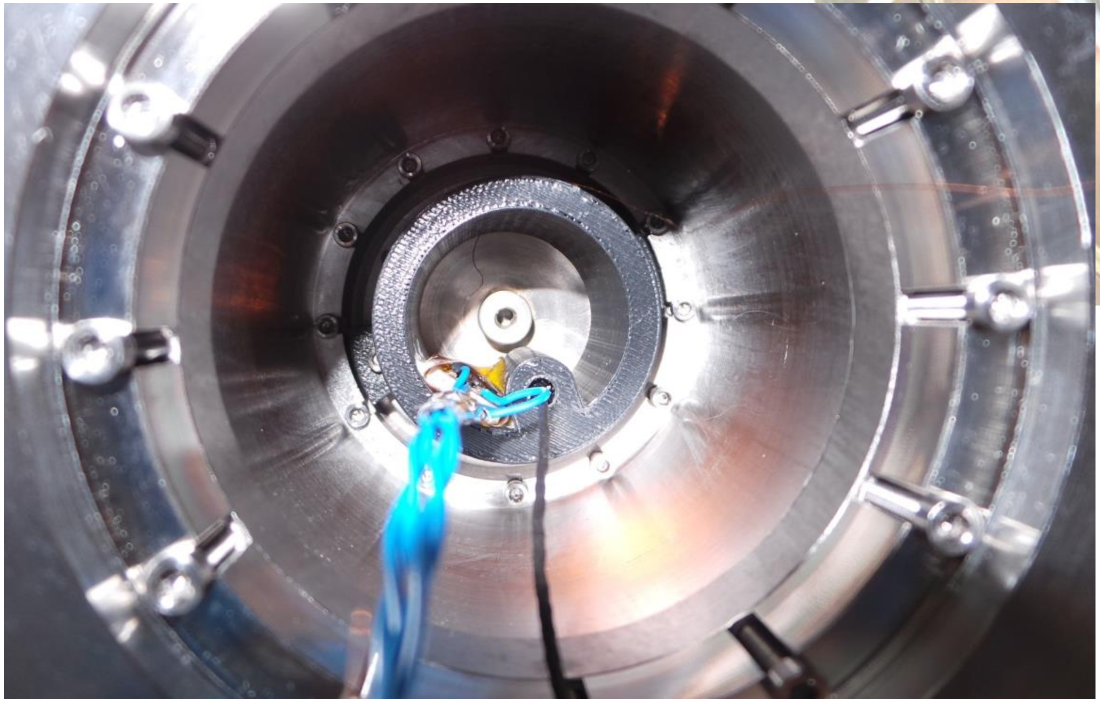




Trapped magnetic flux

- Coil installed below sample
- Flux gate probe measures applied and trapped flux





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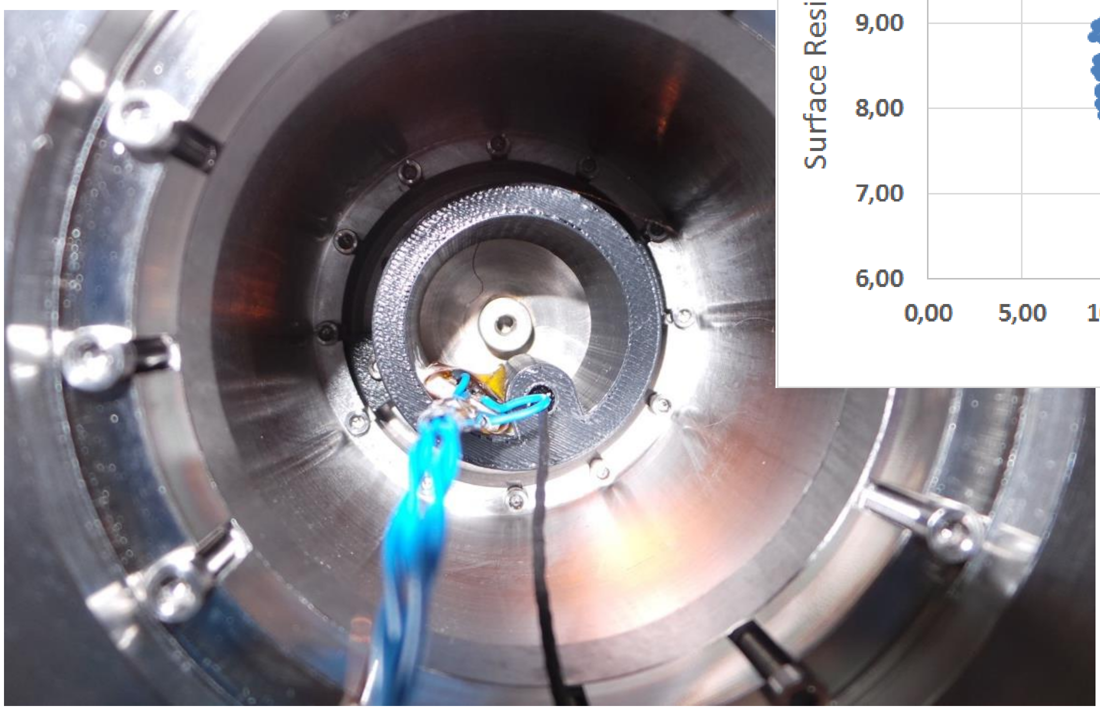
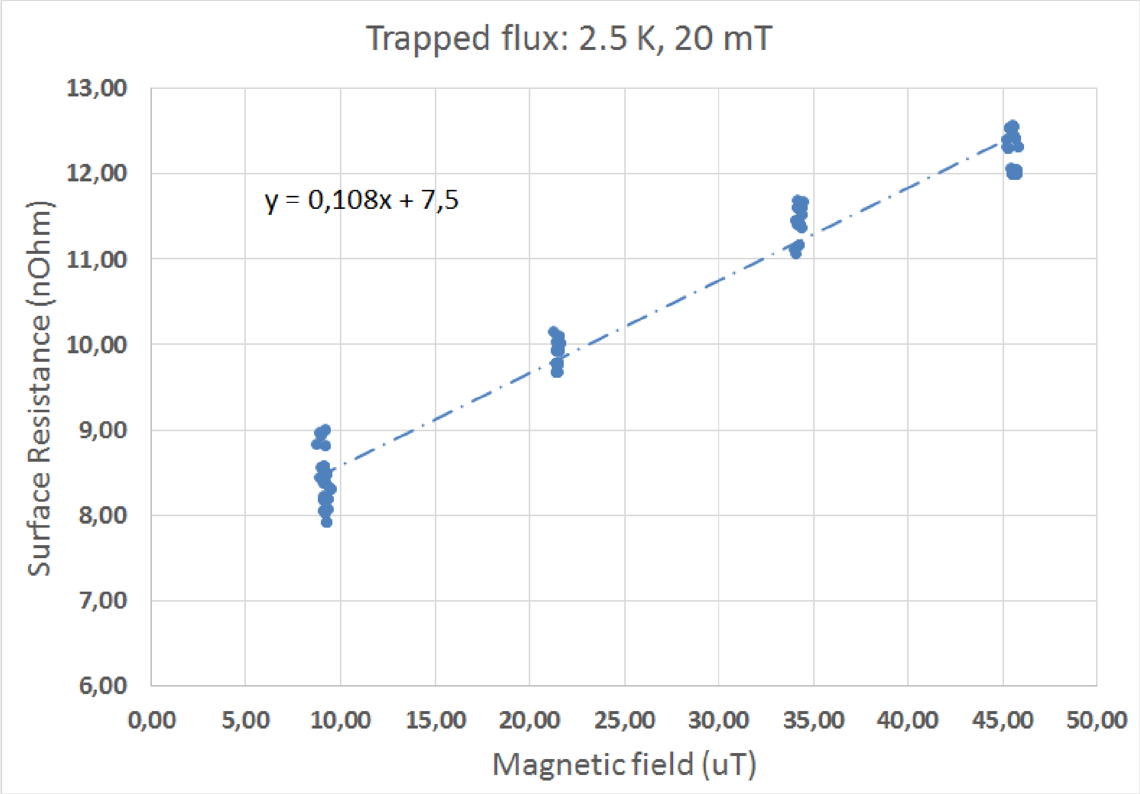
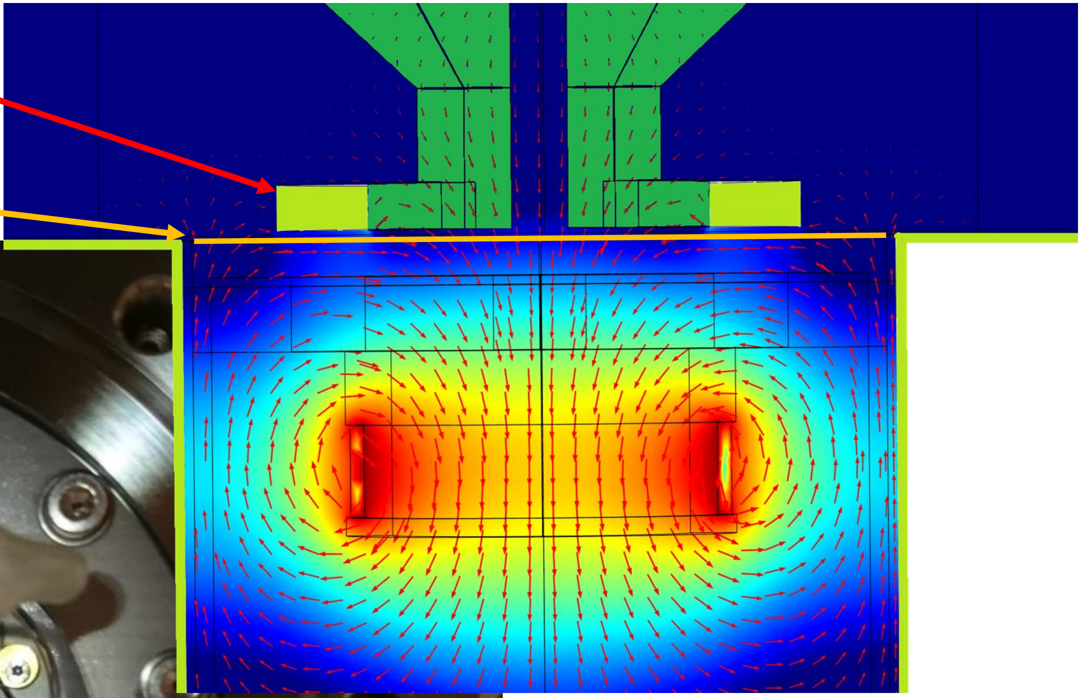


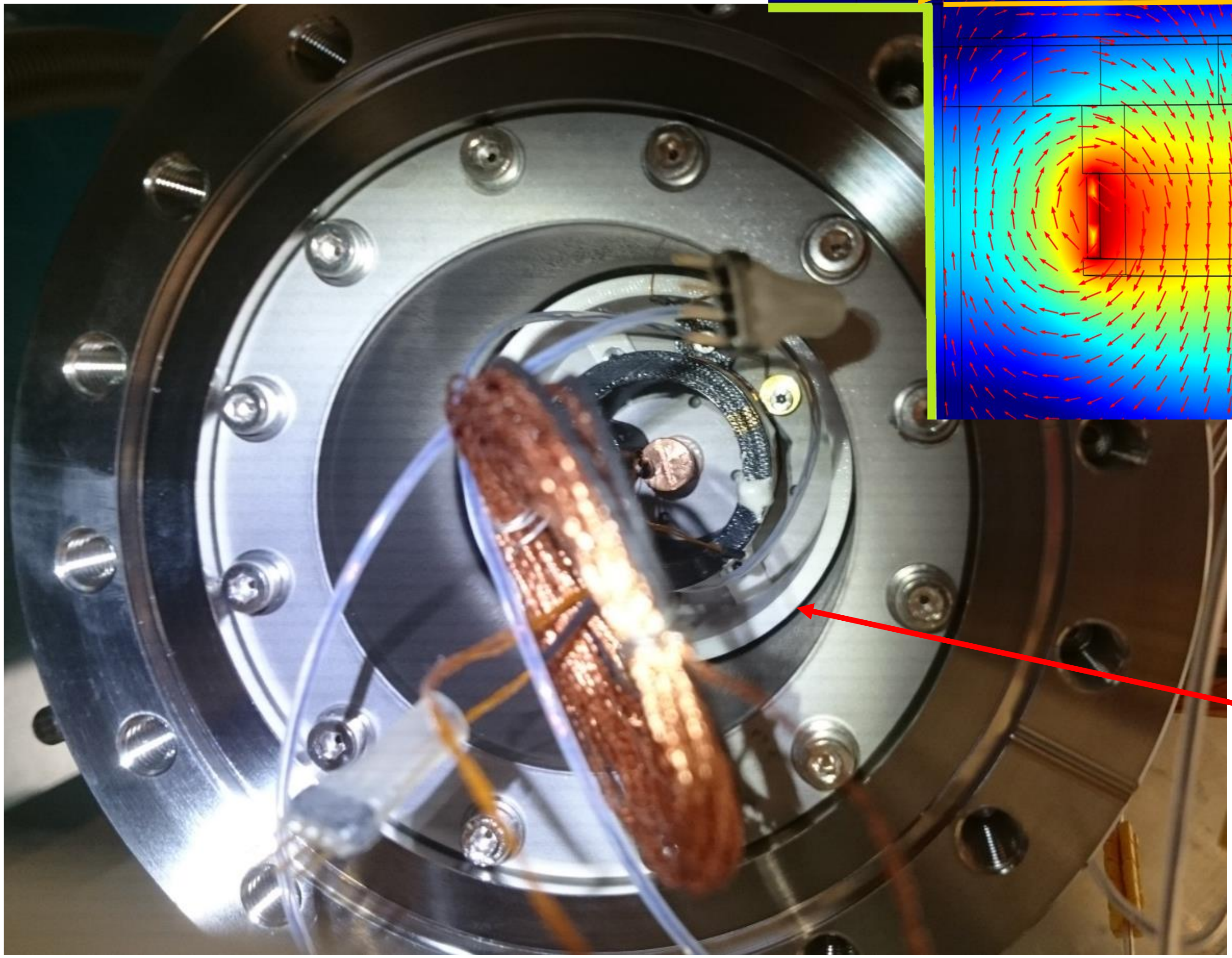


Trapped magnetic flux

QPR pole shoes (SC!)

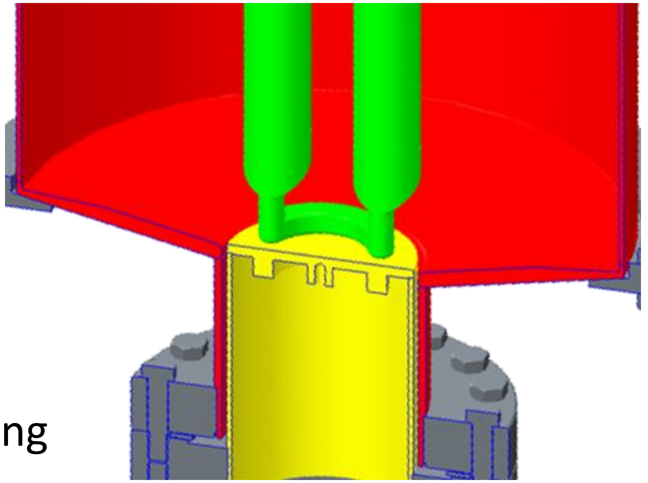
RF surface





2nd coil with reversed field

RF penetration depth



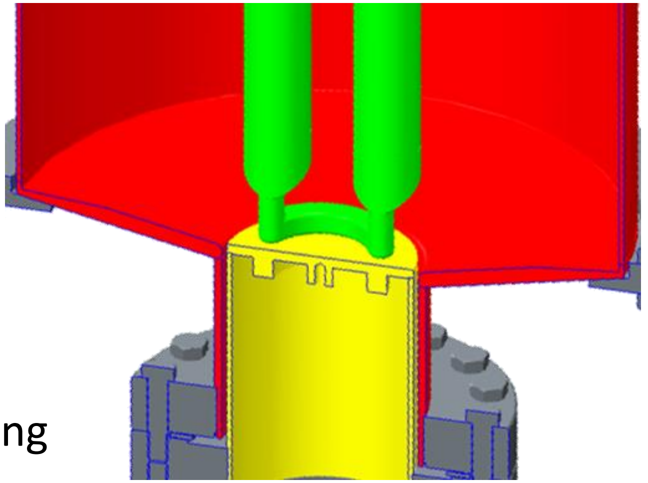
- $\lambda(T) = \frac{\lambda_0}{\sqrt{1-\left(\frac{T}{T_c}\right)^4}}$
- Slater‘s Theorem: $\frac{\Delta f}{f} = \frac{\frac{1}{4}\int_V^{V+\Delta V}\left(\epsilon_0|E|^2-\mu_0|H|^2\right)\,\mathrm{d}V}{U}$

  Electric penetration contribution negligible, $\mathrm{d}V = \mathrm{d}A\;\mathrm{d}\lambda$

  → increasing volume of resonator → frequency decreasing
- $\lambda(T) - \lambda_0 = \Delta\lambda = -\frac{G_{\mathrm{Sample}}}{\pi\mu_0 f^2}\Delta f$
- mean free path from $\lambda(0\ \mathrm{K}) = \lambda_0$

  $\lambda_0(l) = \lambda_L\sqrt{1 + \frac{\pi\xi_0}{2l}}$
- $RRR \approx \frac{l\ [\mathrm{nm}]}{2.7}$

RF penetration depth



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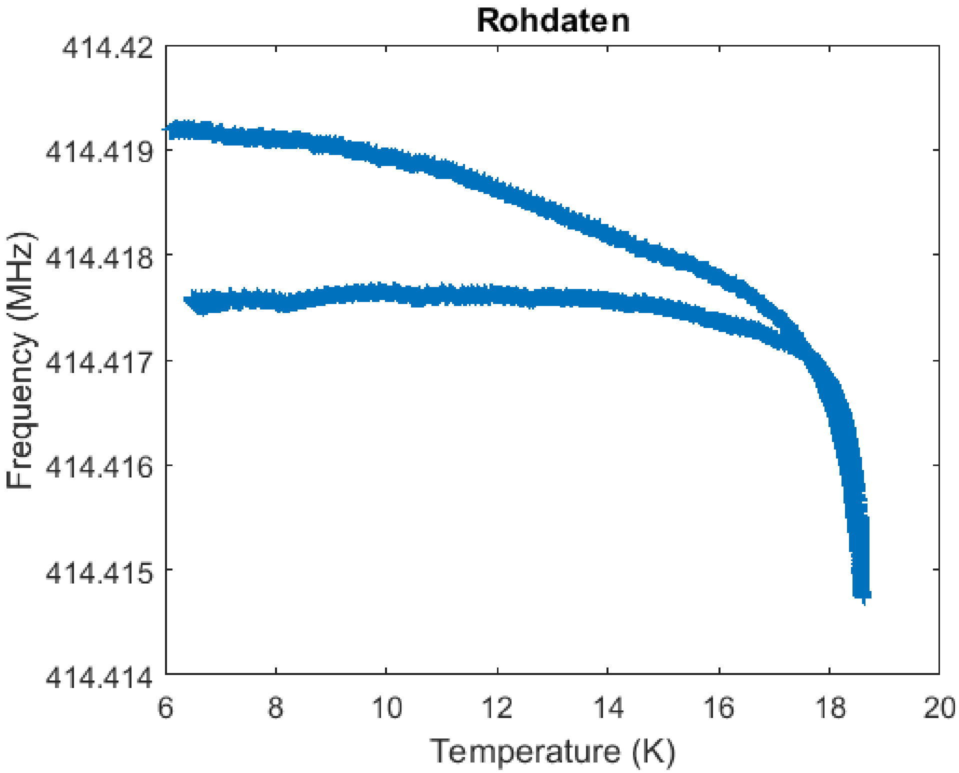
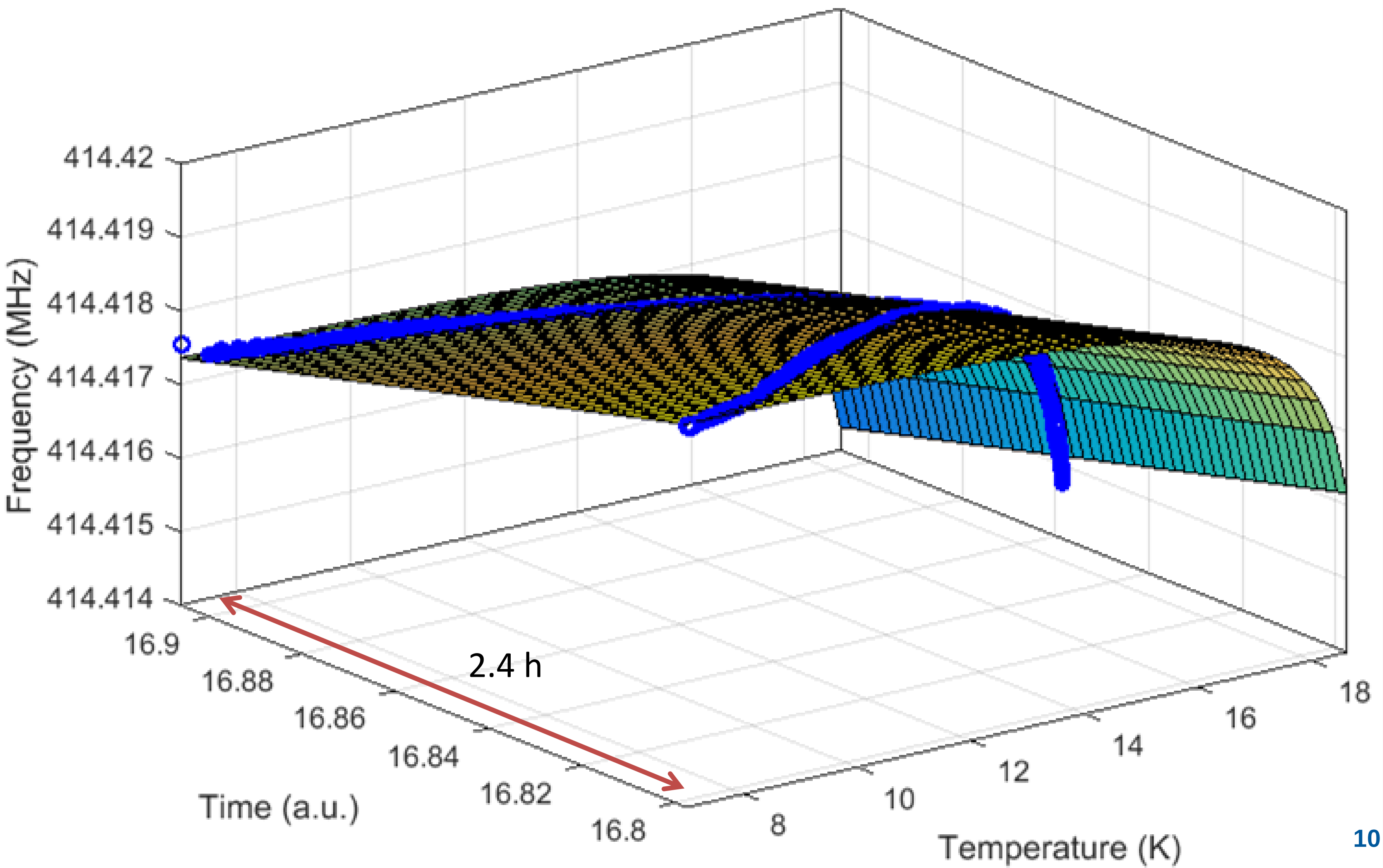


RF penetration depth

- Decreasing helium level → linear drift of frequency



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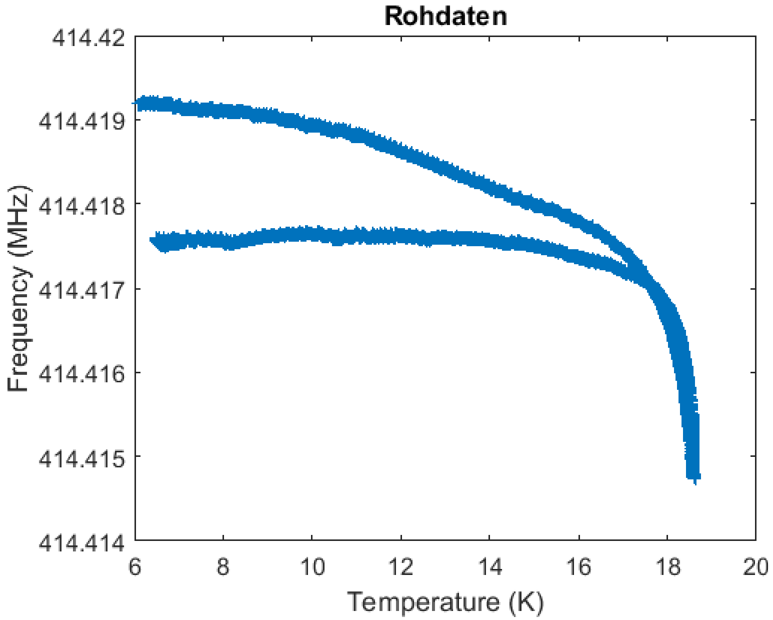
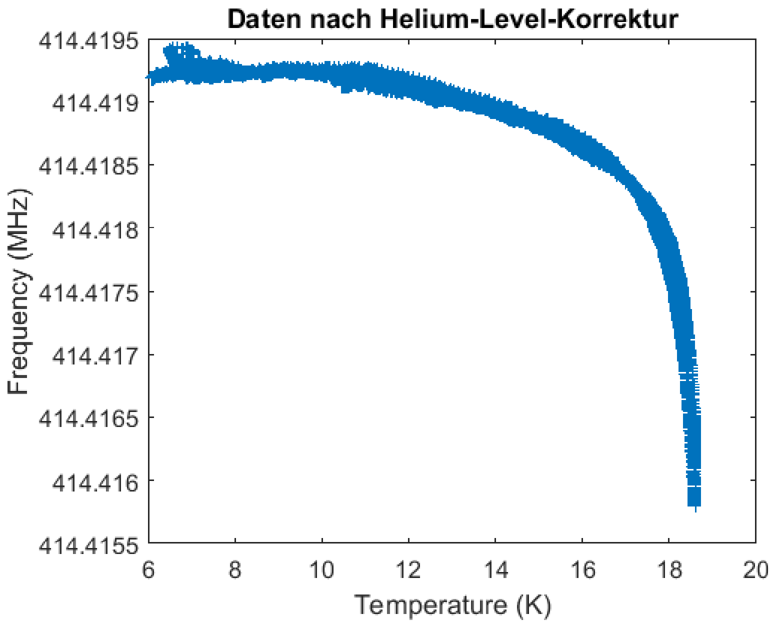
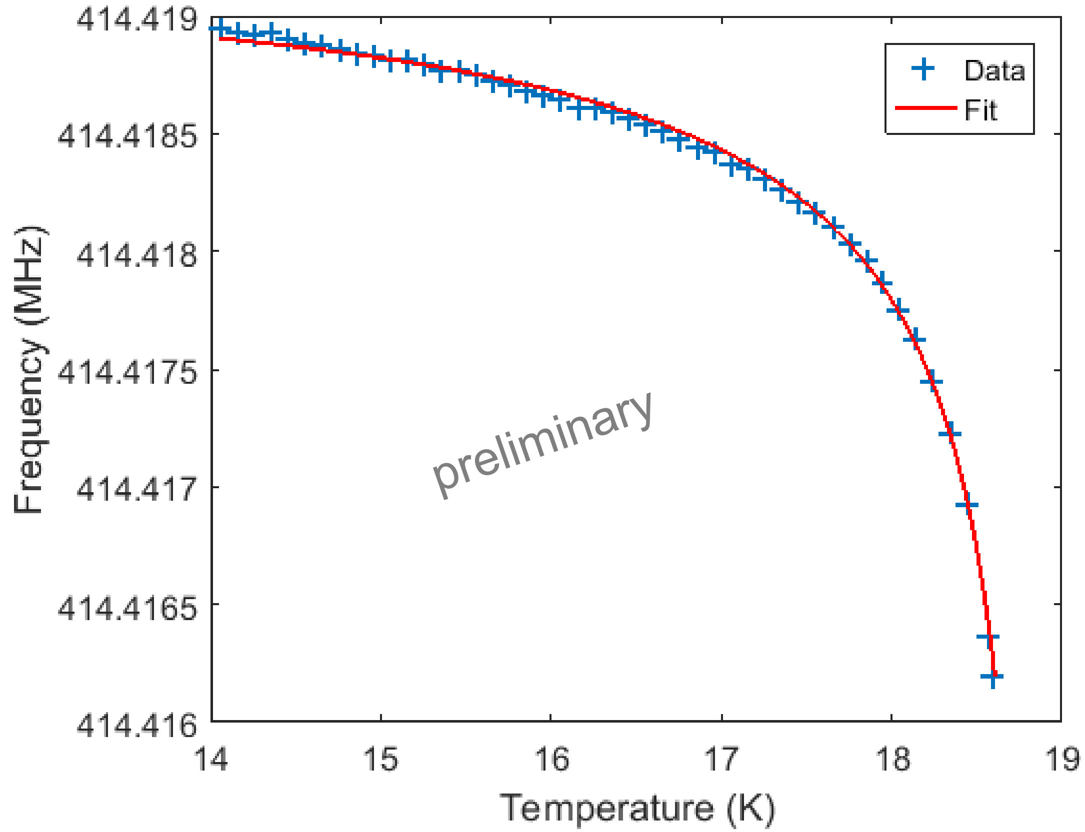






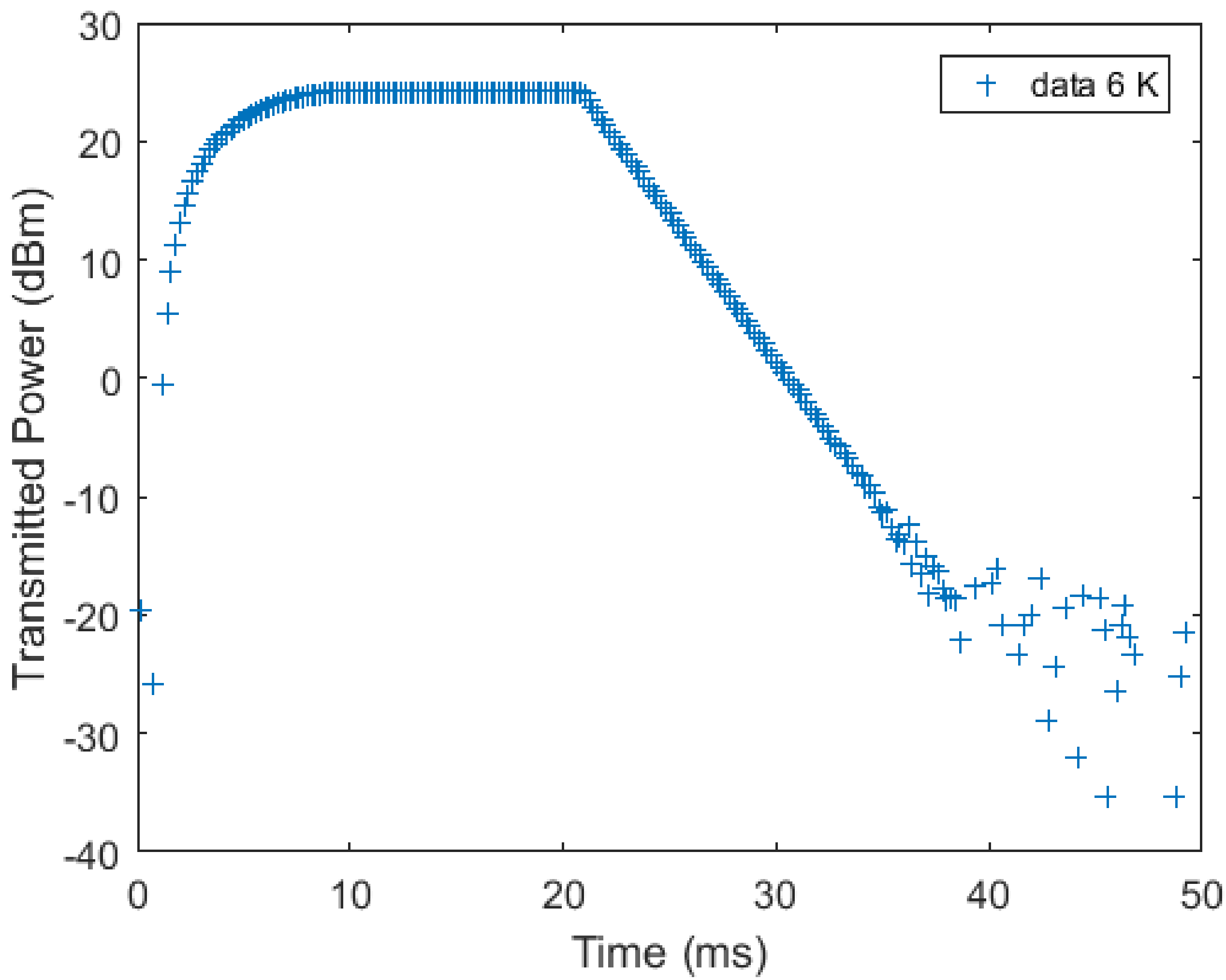
Nb_3Sn sample (provided by Cornell)

$\lambda_L = 90$ nm

$\lambda_0 \approx 140$ nm (from fit)

RF critical field

- $B_c(T) = B_{c,0} \cdot \left(1 - \left(\frac{T}{T_c}\right)^2\right)$
- Single short pulse of RF power → sample quenches



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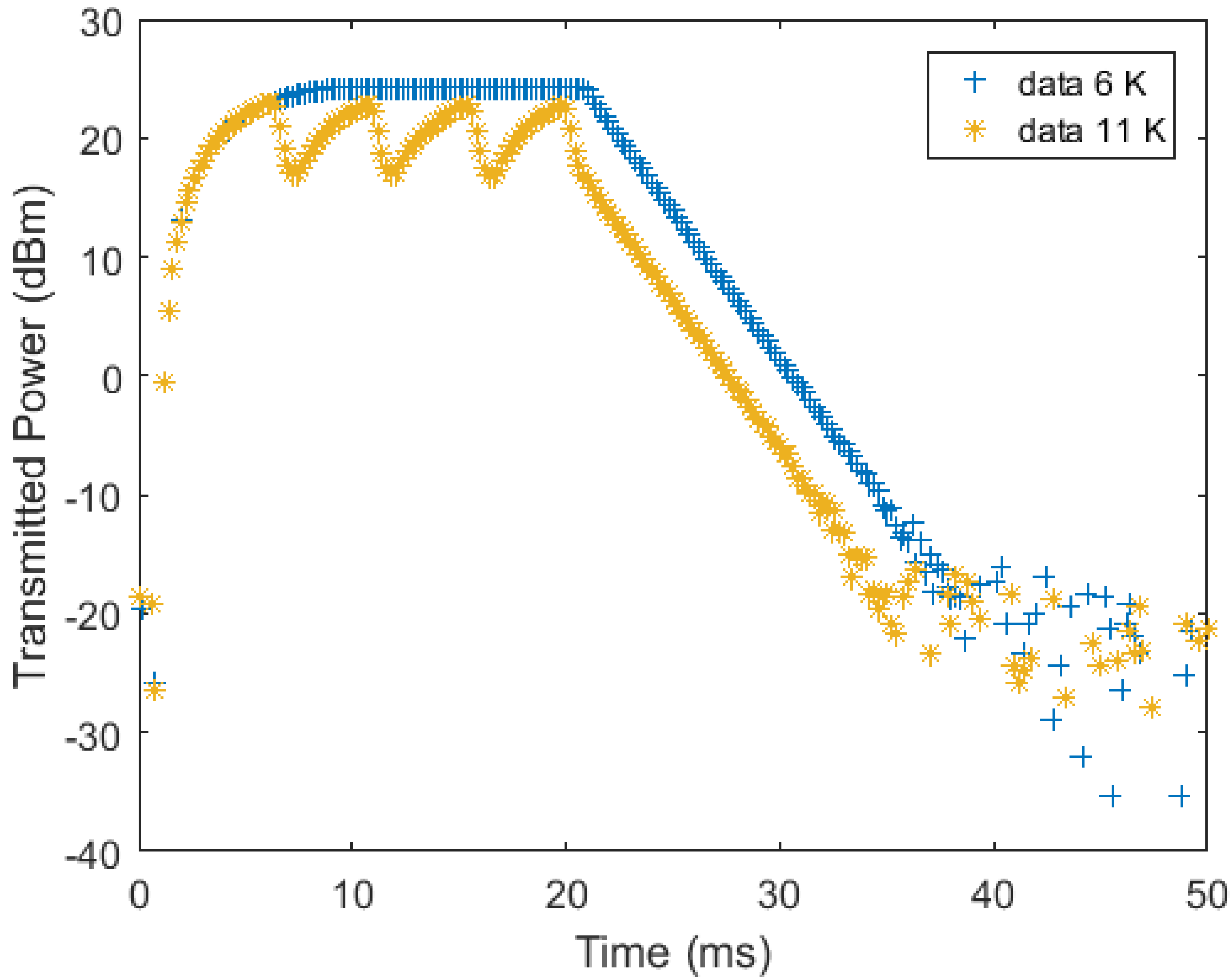

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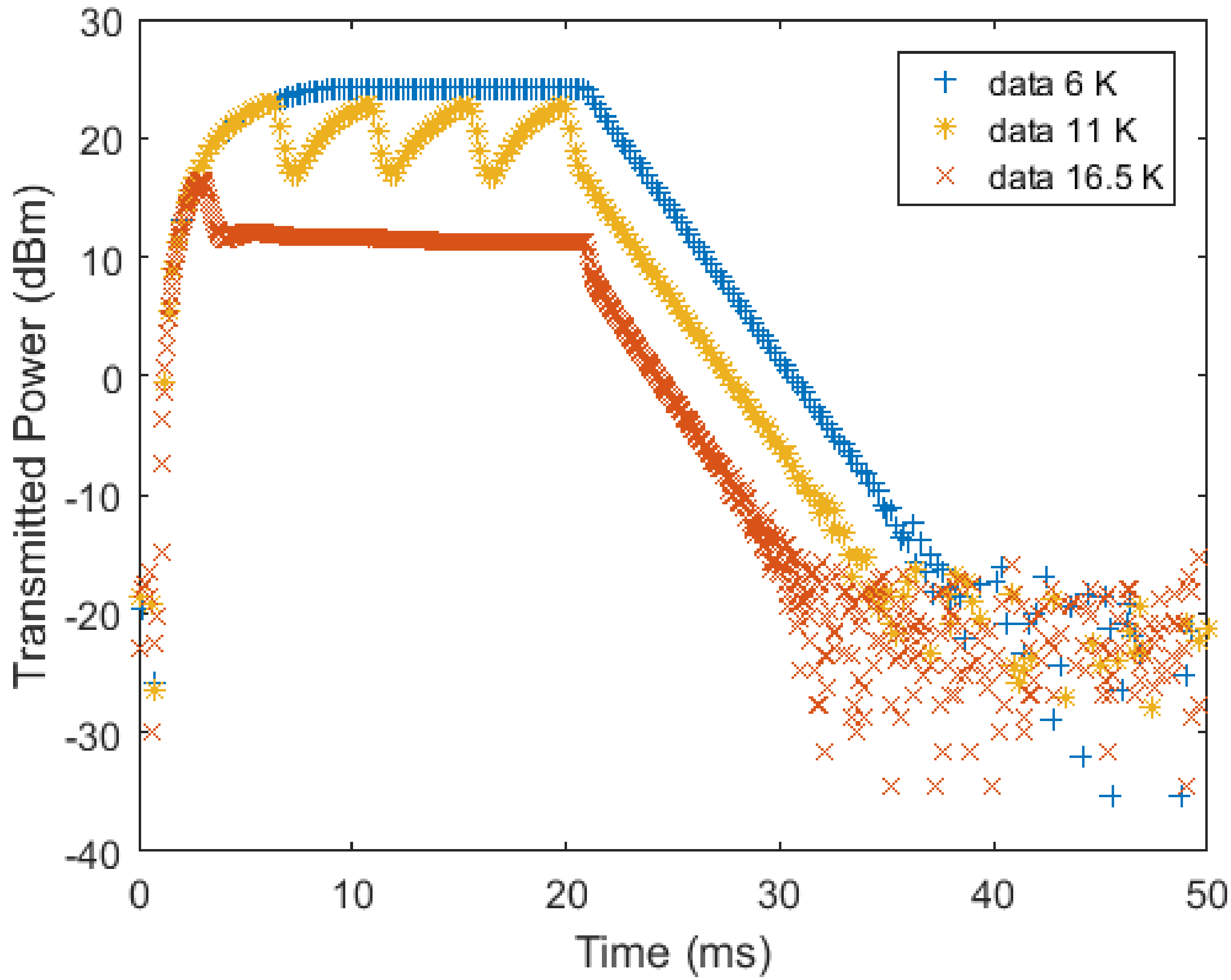
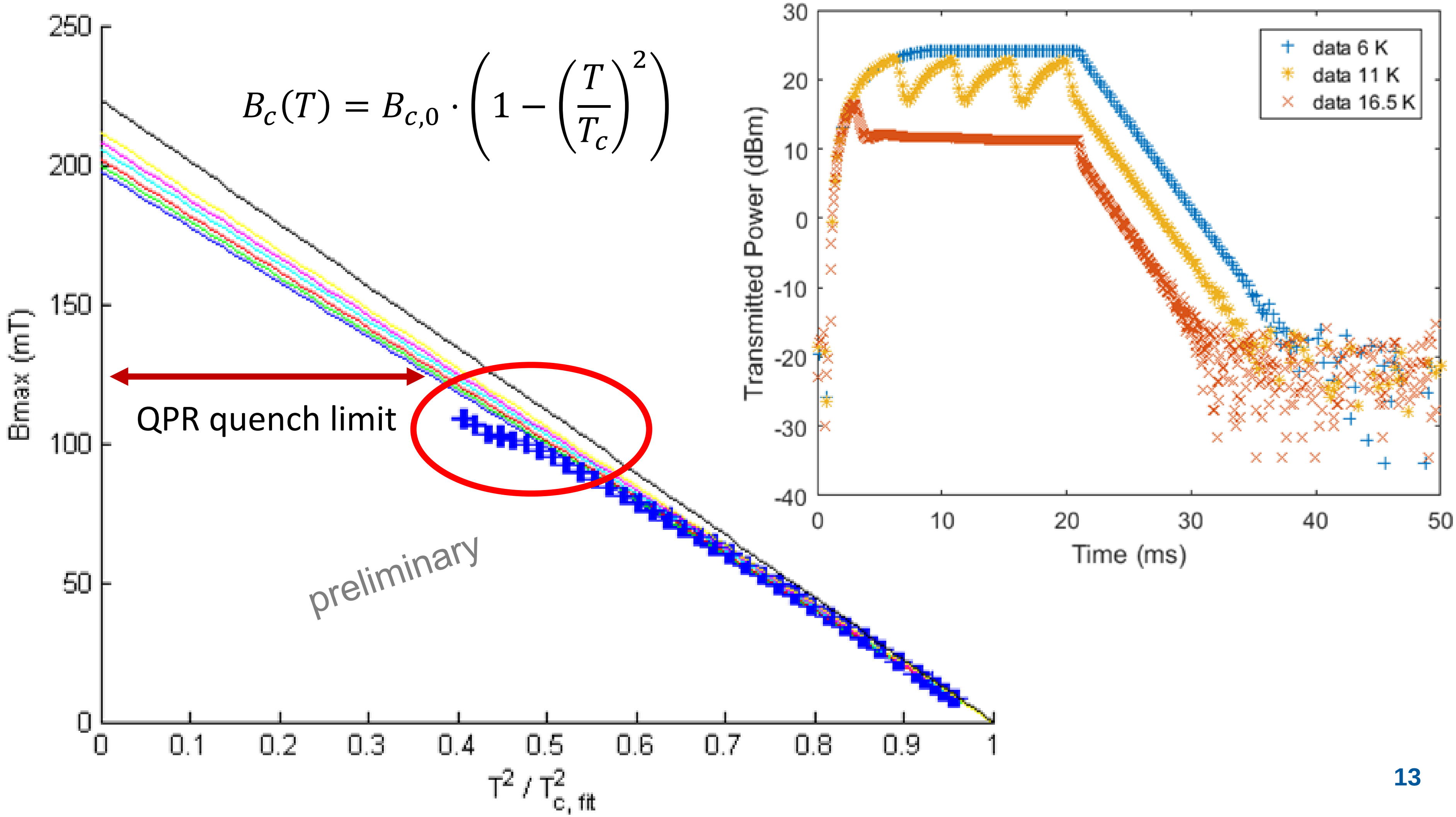


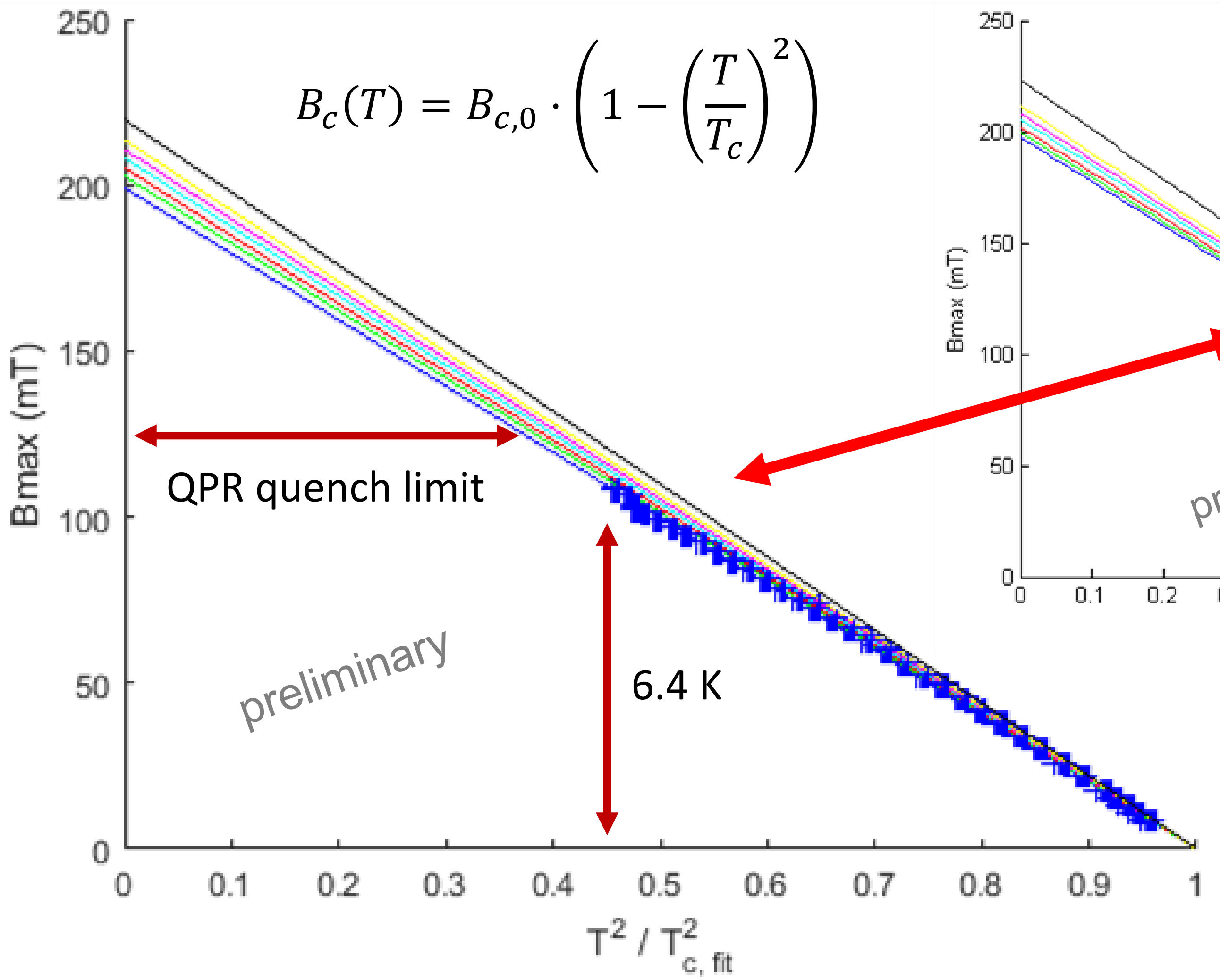
RF critical field

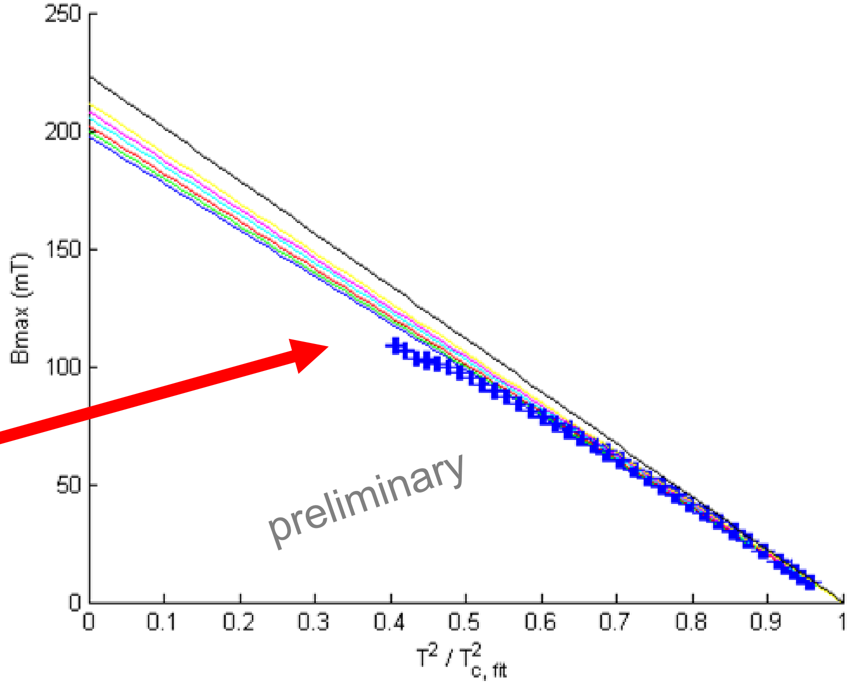
- N-doped Nb sample (provided by Jefferson Lab)
- Significant RF heating at lower temperatures



RF critical field

- Significant RF heating at lower temperatures → correction applied to data
- N-doped Nb sample (provided by Jefferson Lab)
  → no reduction of quench field observed





Summary

- QPR commissioned at 420, 850, 1300 MHz
  - Quench limit at 125 mT
- Automated penetration depth measurement
- Single pulse critical field measurement
- Work ongoing on trapped magnetic flux

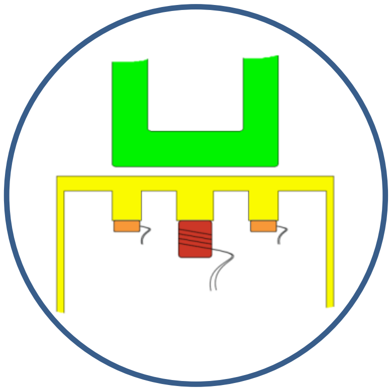
Thank you for your attention!

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

BACKUP SLIDES

HZB QPR

RF-DC compensation technique



- High precision: calorimetric measurement
  - Resolution: sub-nΩ
- Wide temperature range: $T_{min} = T_{LHe}\ ,\ T_{max} > 20\ K$
- Operating at low frequency (420 MHz)
  - Low BCS resistance → sensitivity to R_{res}

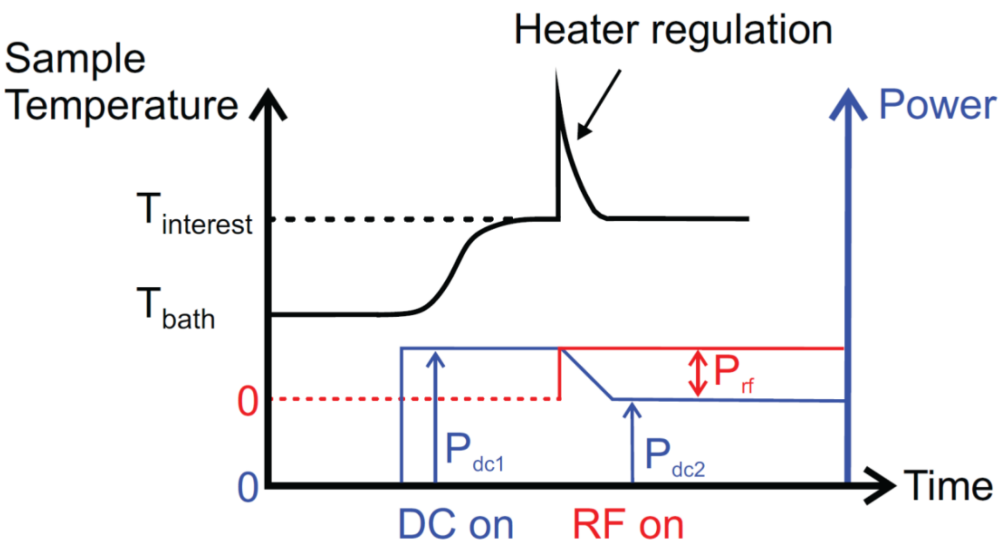
$$P_{\mathrm{RF}} = \frac{1}{2}\iint_{sample} R_S\left|\vec{H}\right|^2 dS$$

$$= R_S\frac{\omega U}{G}$$

$$= P_{\mathrm{DC,1}} - P_{\mathrm{DC,2}}$$

$$\Rightarrow R_S = \frac{G}{\omega U}\left(P_{\mathrm{DC,1}} - P_{\mathrm{DC,2}}\right)$$

$$= c(\omega)\cdot\frac{P_{\mathrm{DC,1}}-P_{\mathrm{DC,2}}}{P_{\mathrm{RF\ pickup}}}$$

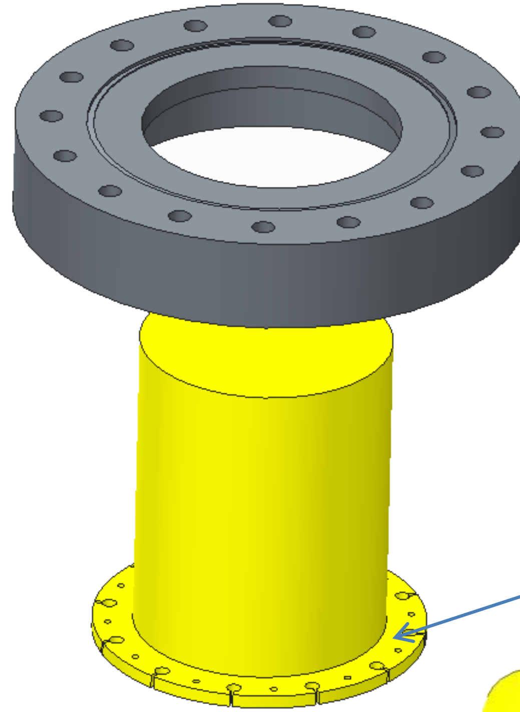


[S. Aull, „High Resolution Surface Resistance Studies“, SRF 2013]

Alternative calorimetry chamber

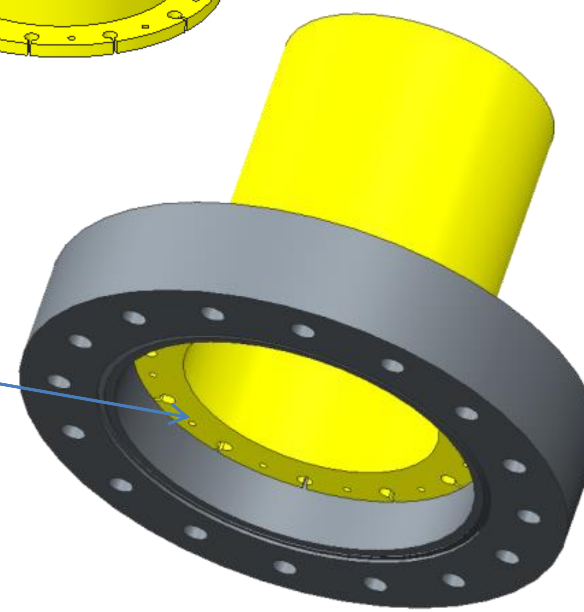
HZB Helmholtz Zentrum Berlin

- Pure Nb sample
  → high temperature treatments possible
  - baking, doping, coating
- UHV tight system
  → Indium wire gasket reproducible
- Height adjustment possible
  → compatible to CERN QPR

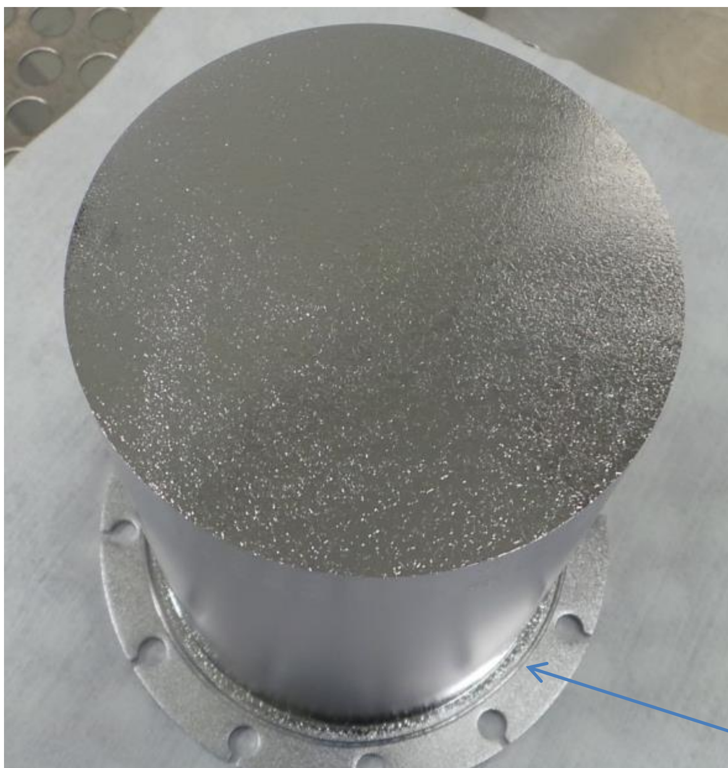


Double sided CF100 flange

Indium wire



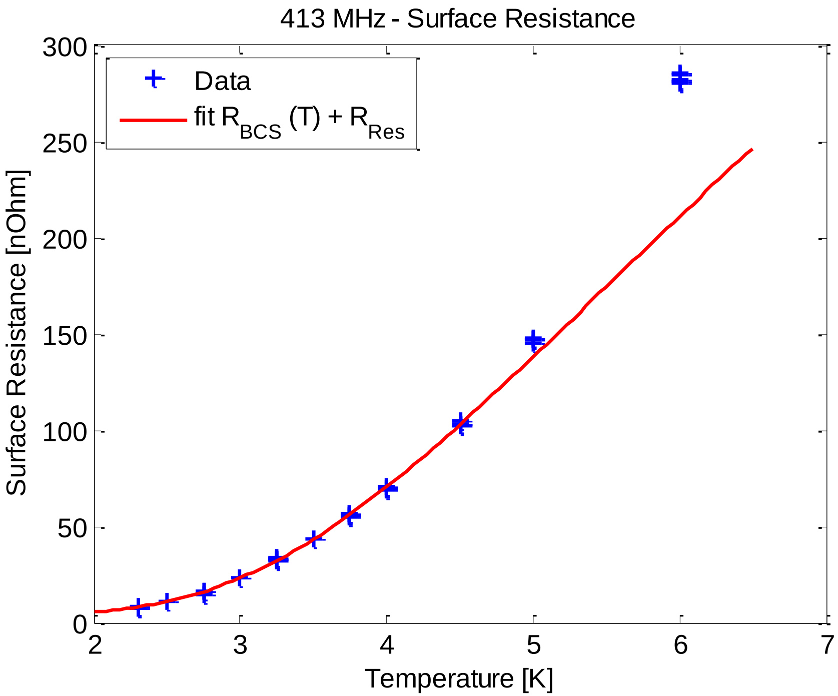
additional T-sensors

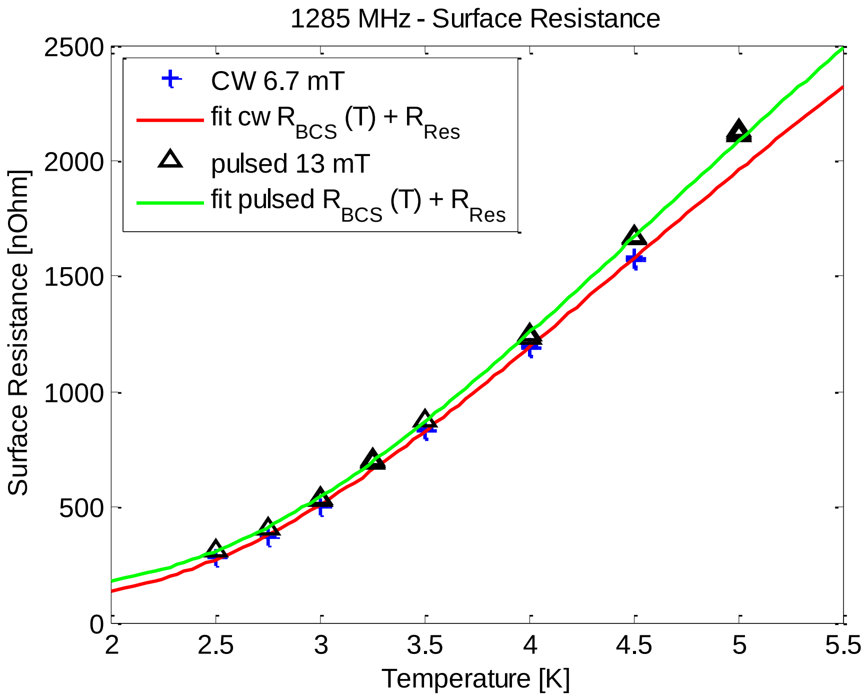


Indium wire

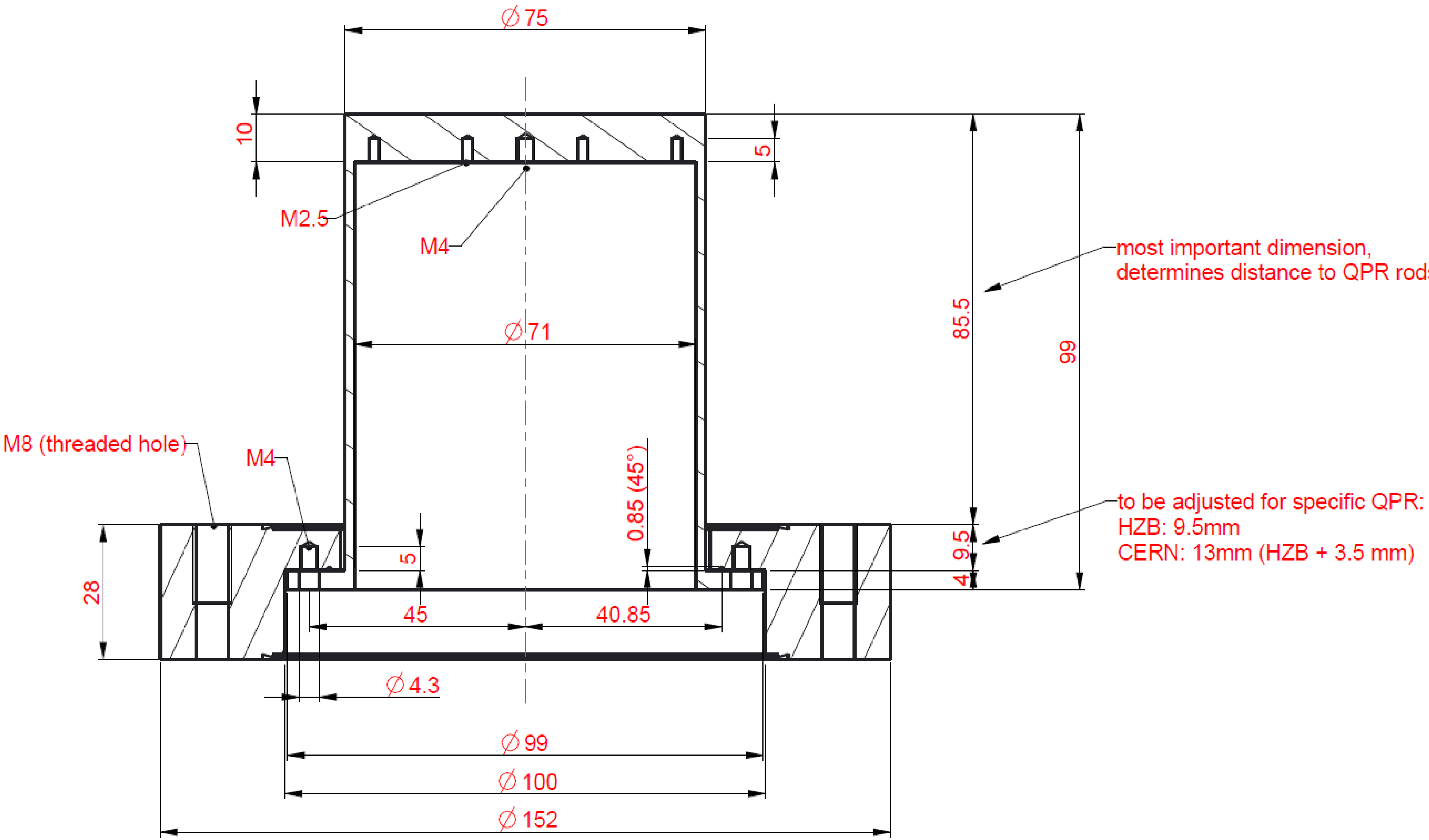
Commissioning of alt. calorimetry chamber

$$R_S = R_{BCS} + R_{res} = \frac{A\omega^2}{T}\exp\left(-b\frac{T_c}{T}\right) + R_{res}$$





	413 MHz 16 mT, cw	1285 MHz 6.7 mT, cw	1285 MHz 13 mT, 30% DF
$A\left[\frac{\mu\Omega\ \mathrm{K}}{(\mathrm{GHz})^2}\right]$	4.1 ± 0.2	2.86 ± 0.13	3.37 ± 0.15
b	2.01 ± 0.03	1.62 ± 0.03	1.68 ± 0.03
R_{res} [nΩ]	4.3 ± 0.5	83 ± 12	136 ± 12



∅75
10
5
M2.5
M4
most important dimension,
determines distance to QPR rods
85.5
99
∅71
M8 (threaded hole)
M4
0.85 (45°)
to be adjusted for specific QPR:
HZB: 9.5mm
CERN: 13mm (HZB + 3.5 mm)
28
5
9.5
4
45
40.85
∅4.3
∅99
∅100
∅152

Alternative calorimetry chamber