Activities with the quadrupole resonator at HZB

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Done most of the work

Master thesis
Start of PhD thesis

PhD thesis

EuCARD-2
3rd Annual WP12 Meeting at STFC Daresbury Laboratory
April 4th and 5th 2016

Contents

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- Motivation
- QPR measurement principle
- Commissioning results
- Alternative sample chambers
- Example measurements
- Outlook

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Characterization of superconducting samples

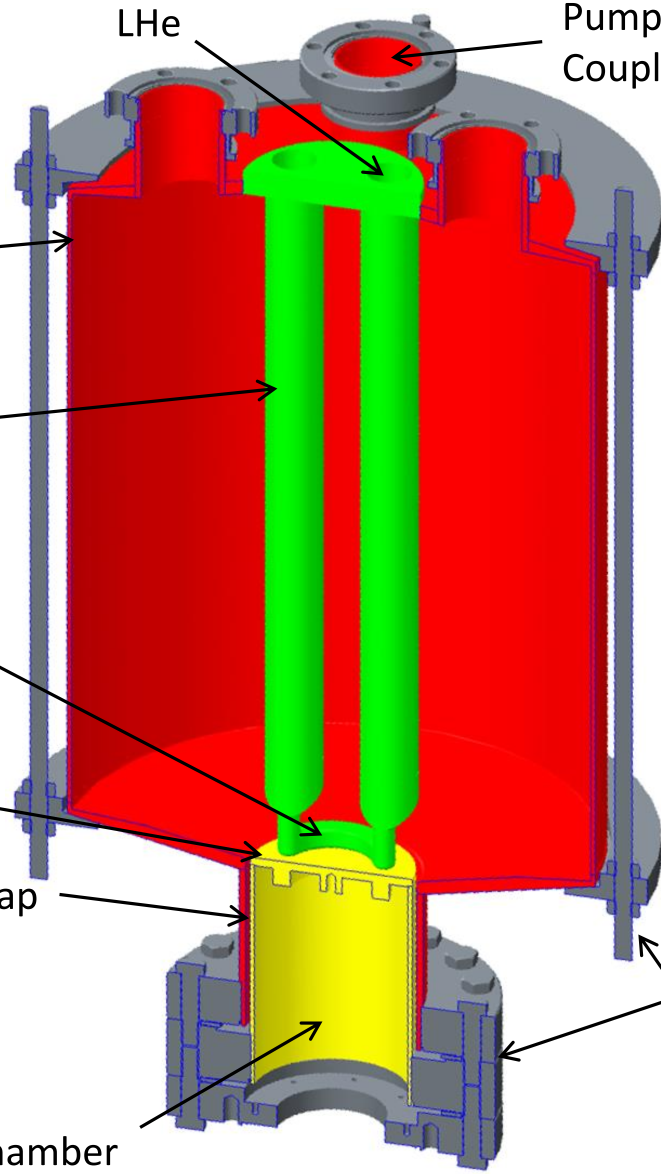
- Study „new“ superconductors
  - Thin films
  - Multilayer films
  - (enhanced Nb)

- What does an ideal tool look like?
  (without going through the hassle of building an entire cavity)
  - Small and flat samples, easy to change
  - Measure RF surface resistance
  - Wide parameter space quickly available
    - $\omega,\ B_{RF},\ T$
  - High resolution: $Q_0 \approx 3 \cdot 10^{11} \leftrightarrow R_S \approx 1\ \mathrm{n\Omega}$
  - Further sc properties
    - RF penetration depth, B_c, RRR, m.f.p., thermal conductivity

- Milestone 78 delivered in 10/2015

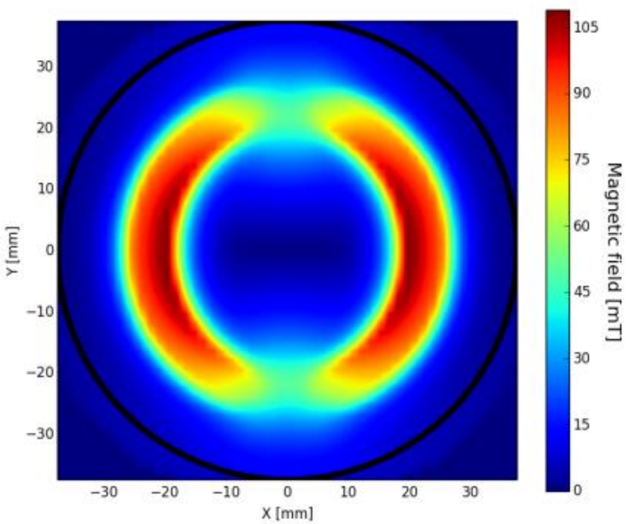
The Quadrupole Resonator (QPR)

- System based on CERN design
  EPAC ´98, Rev. Sci. Instrum. 74, 3390-3393 (2003)
- Optimized RF parameters
- Cavity and 4 hollow rods made of Nb RRR 300
- 433 MHz or harmonics excited with loop antenna

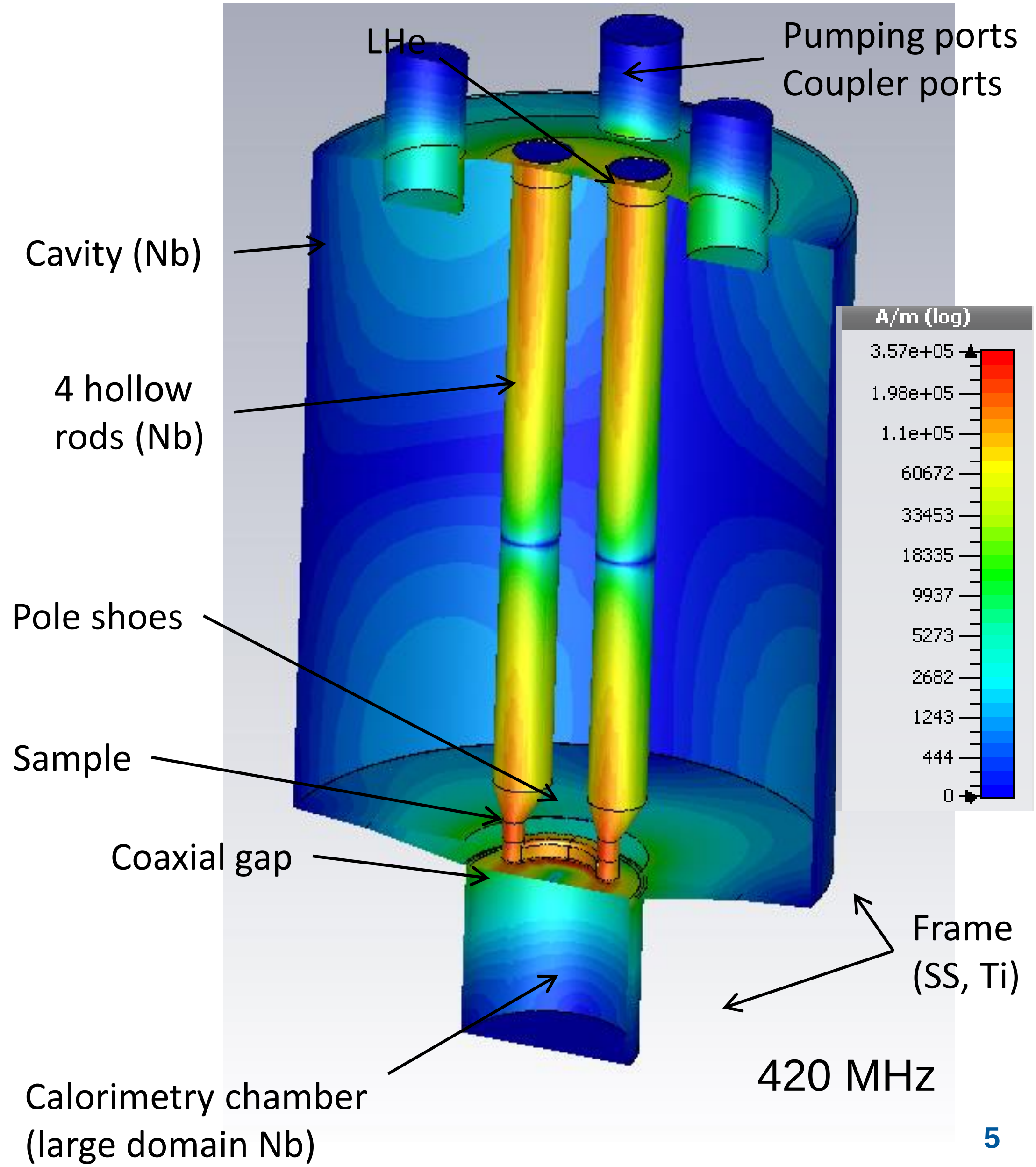


The Quadrupole Resonator (QPR)

- Pole shoes focus magnetic field on sample

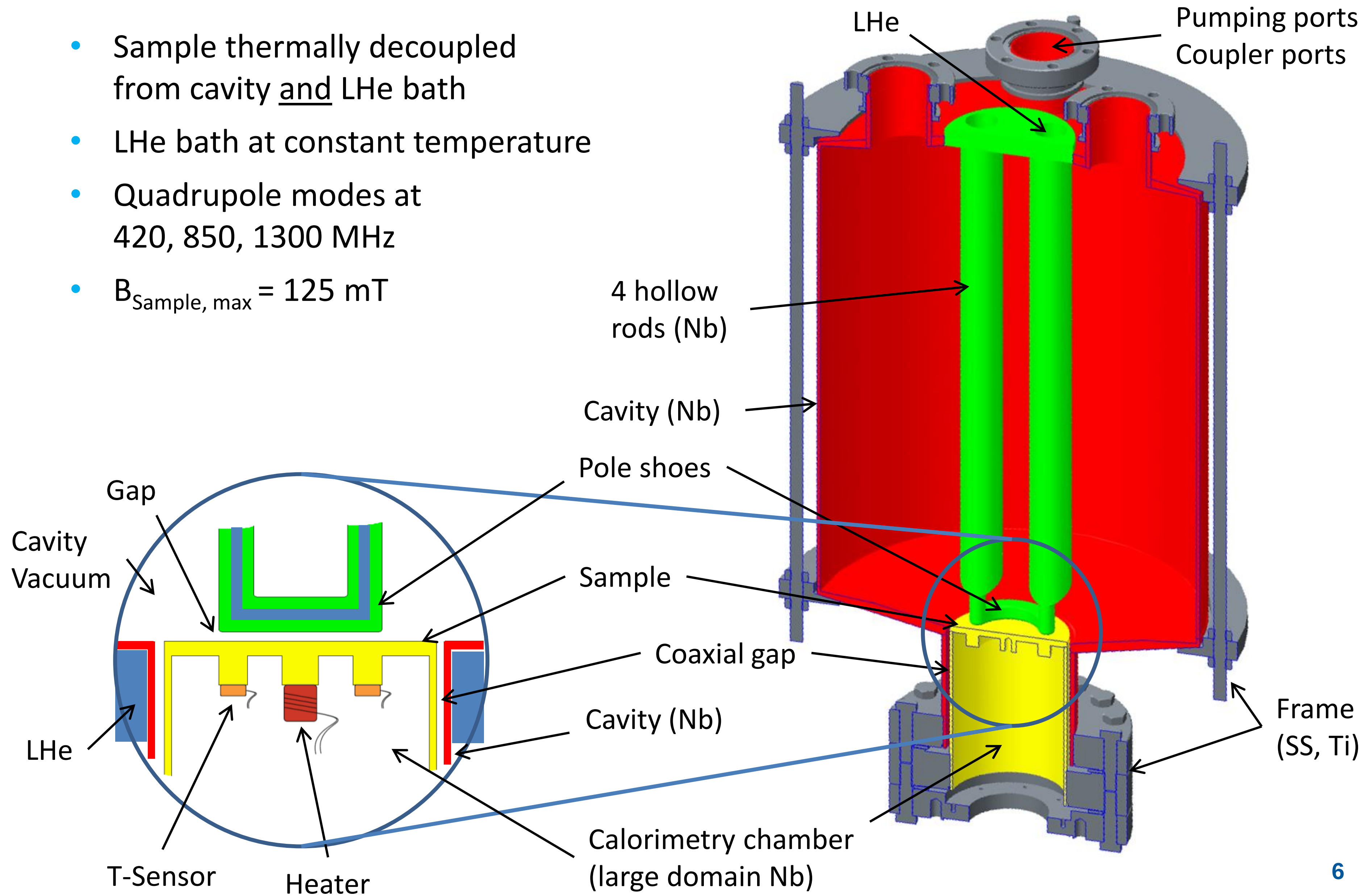


- Ring shaped region of sample illuminated
- Obtain geometry factor from simulation



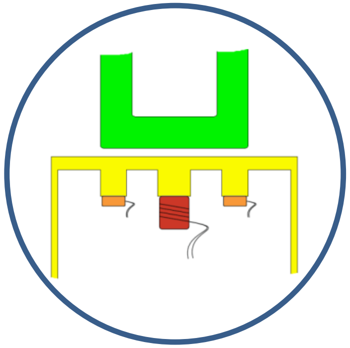
The Quadrupole Resonator (QPR)

- Sample thermally decoupled from cavity and LHe bath
- LHe bath at constant temperature
- Quadrupole modes at 420, 850, 1300 MHz
- $B_{Sample, max} = 125$ mT



RF-DC compensation technique

- High precision: calorimetric measurement
  - Resolution: sub-nΩ
- Wide temperature range: 1.8 K up to $T > T_{c,\,Nb}$



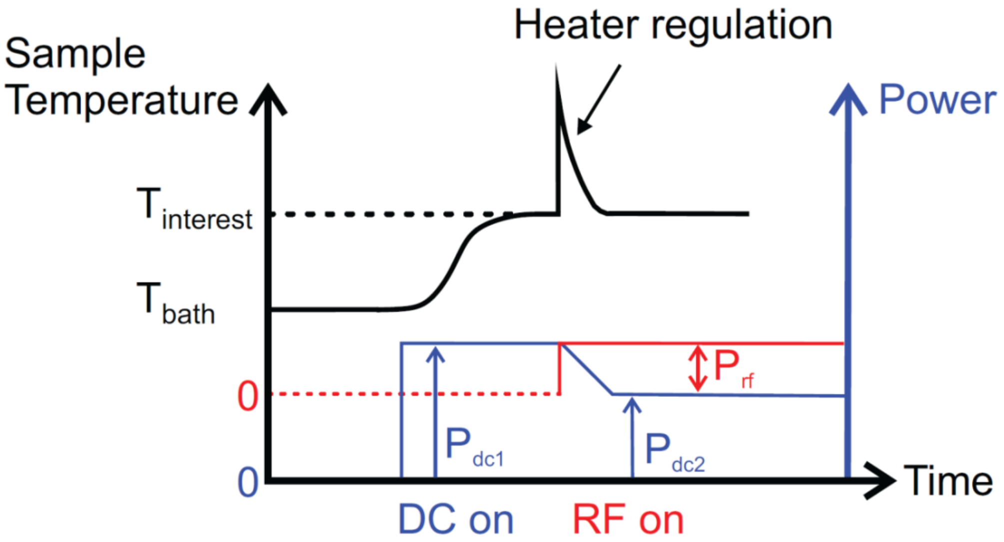
$$P_{\mathrm{RF}} = \frac{1}{2} \iint_{sample} R_S \left|\vec{H}\right|^2 dS$$

$$P_{\mathrm{RF}} = R_{\mathrm{S}} \frac{\omega U}{G}$$

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

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

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



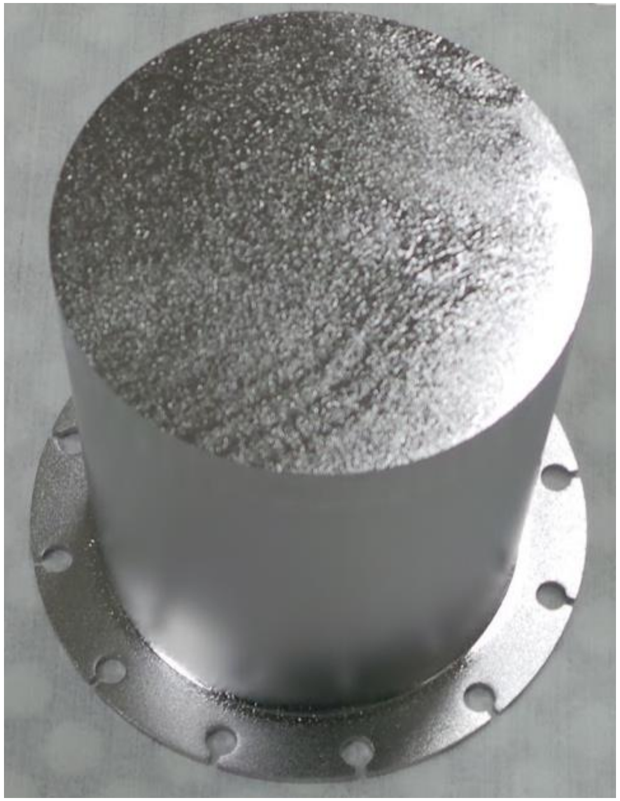
[S. Aull, „High Resolution Surface Resistance Studies“, SRF 2013]

Cryostat and insert with QPR

Clean room assembly

Mounting in the vertical test stand in the HoBiCaT bunker

Niobium samples



Nb: Polychristalline RRR 300

BCP

+ High Temperature bake

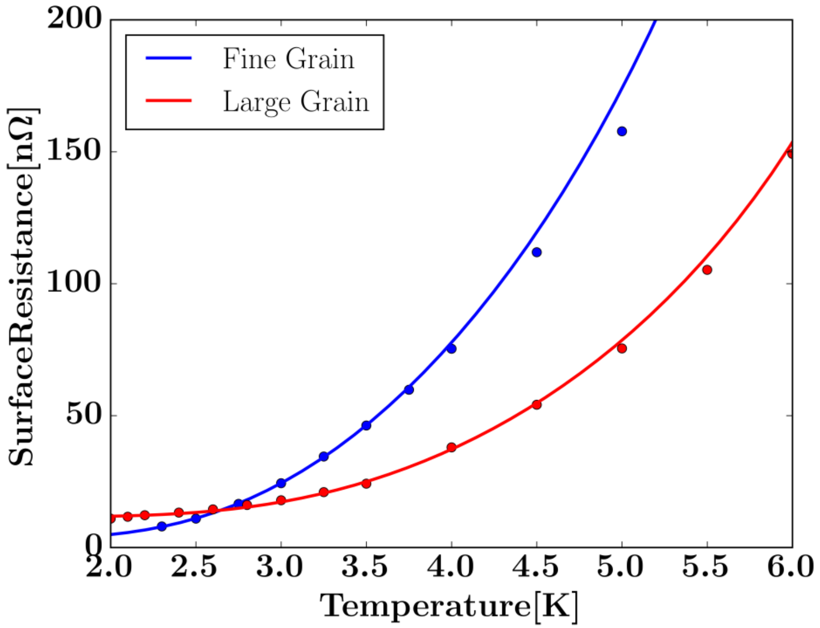
Nb: Large Grain RRR 300

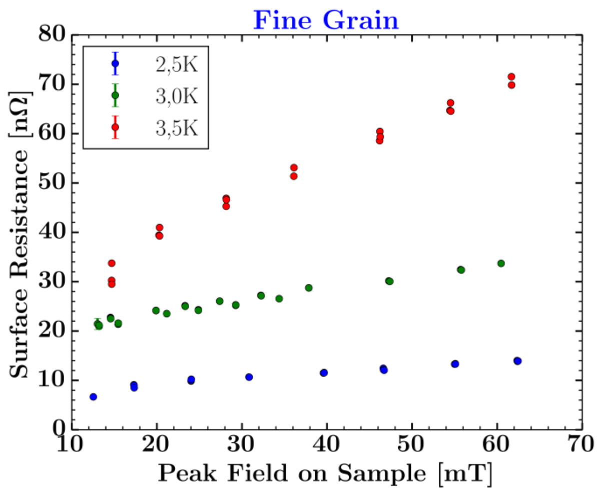
BCP

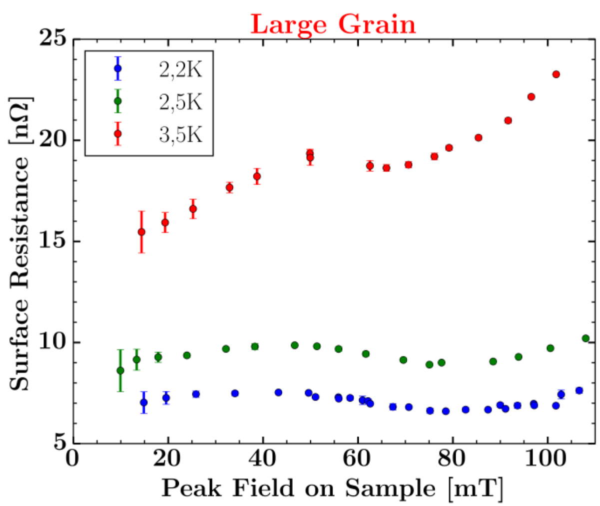
+ High Temperature bake

+ 120°C bake

Commissioning results



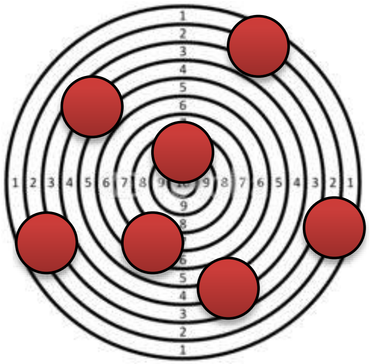




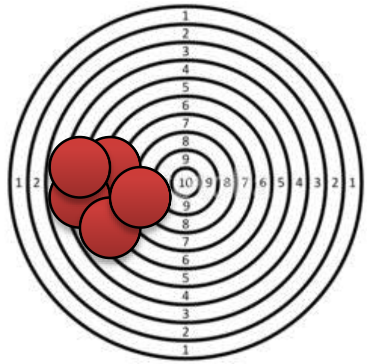
	Fine Grain BCP + HT	Large Grain BCP + HT +120°C
Energy gap	1.8 k_BT_C	2.1 k_BT_C
Electron m.f.p	68 nm	15 nm
Residual Res.	3.1 nΩ	7.6 nΩ

Status of the apparatus

low precision
low accuracy
low resolution



high precision
low accuracy
low resolution



low precision
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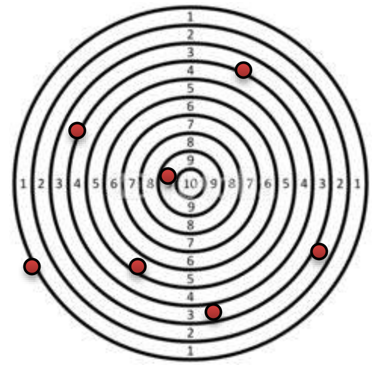

high precision
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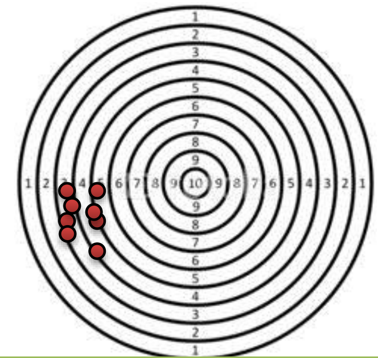

low precision
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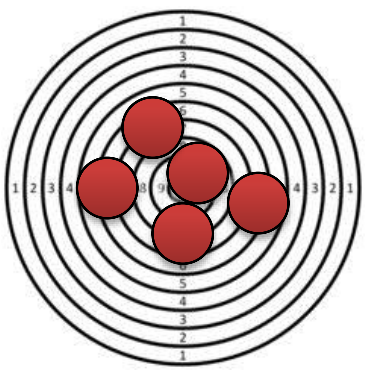

high precision
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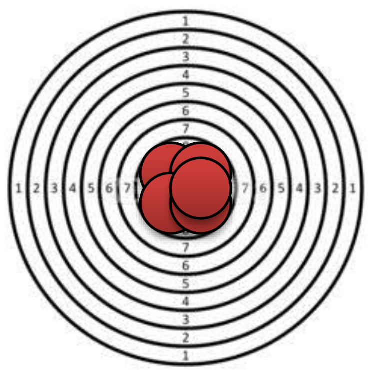

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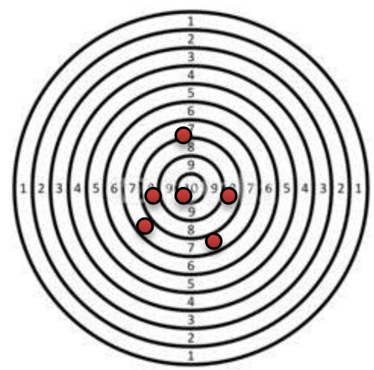

high precision
high accuracy
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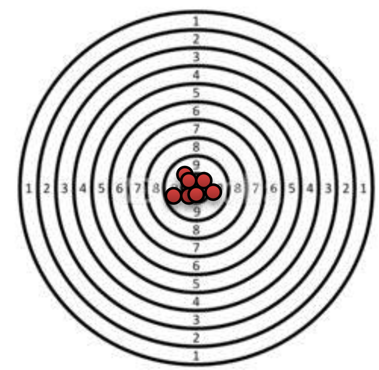
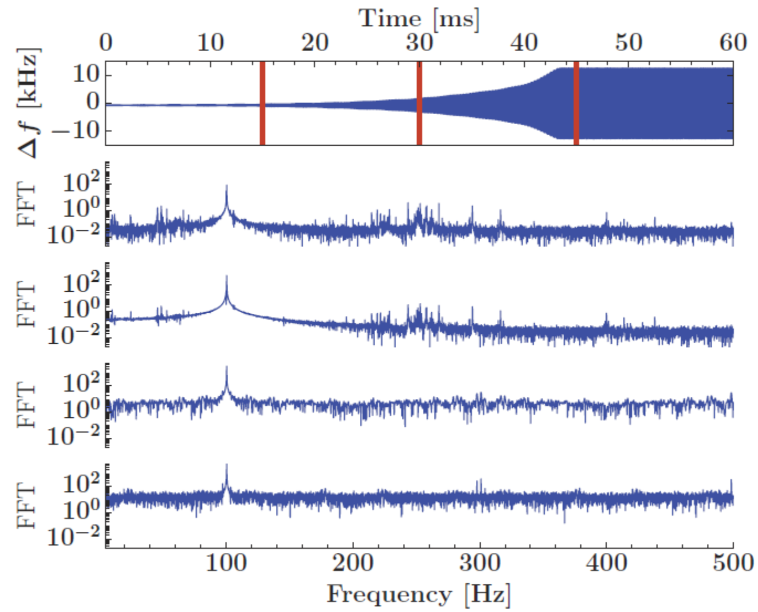


- **Systematic errors still unresolved**
- **Parallelity of gap critical**
- **Concentricity of rods and sample inportant**

PLL feedback signal

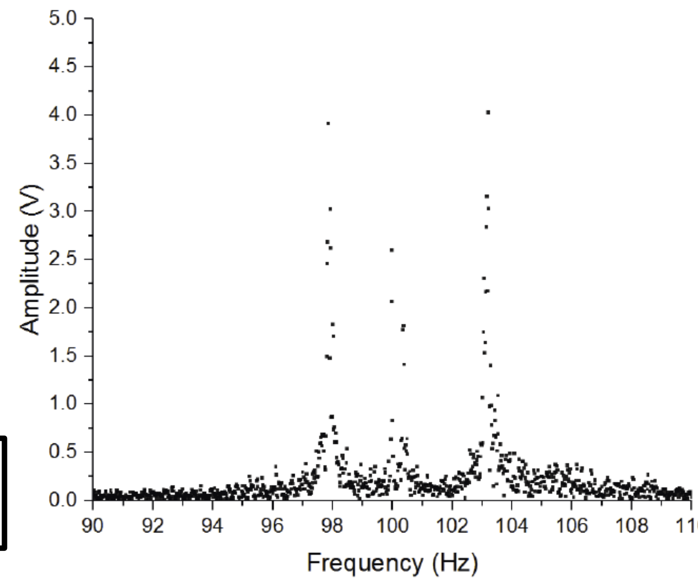


Microphonics is an issue

- Ponderomotive excitations observed
- Oscillation of the rods has resonance at 100 Hz (double mains frequency)
- Mode is always excited and needs to be compensated by PLL
- Complications, esp in pulsed OP

Countermeasures

- done: increased bandwidth of input antenna
- better: passive damping or piezo tuning



measured with geophones at warm resonator

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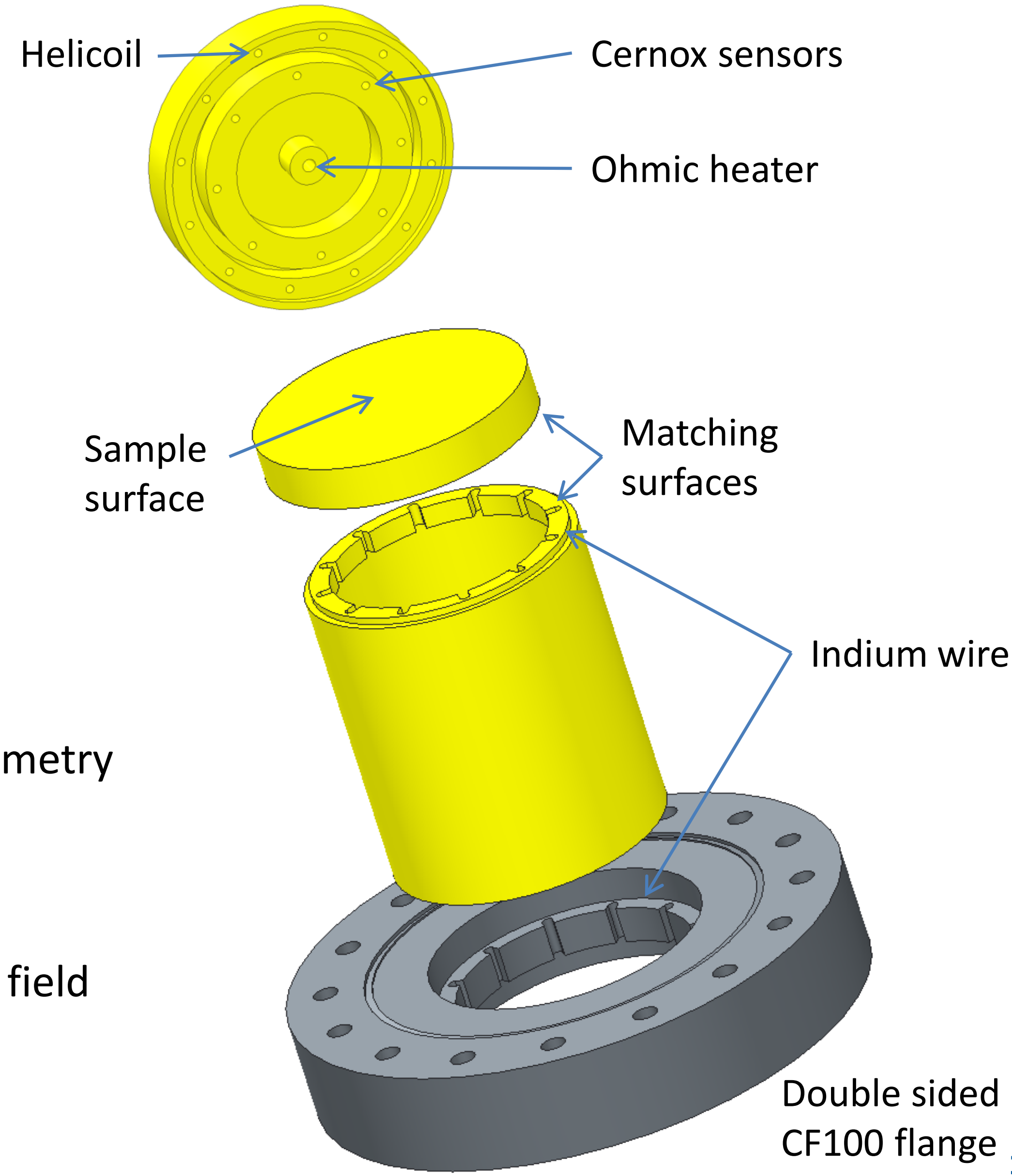
Motivation

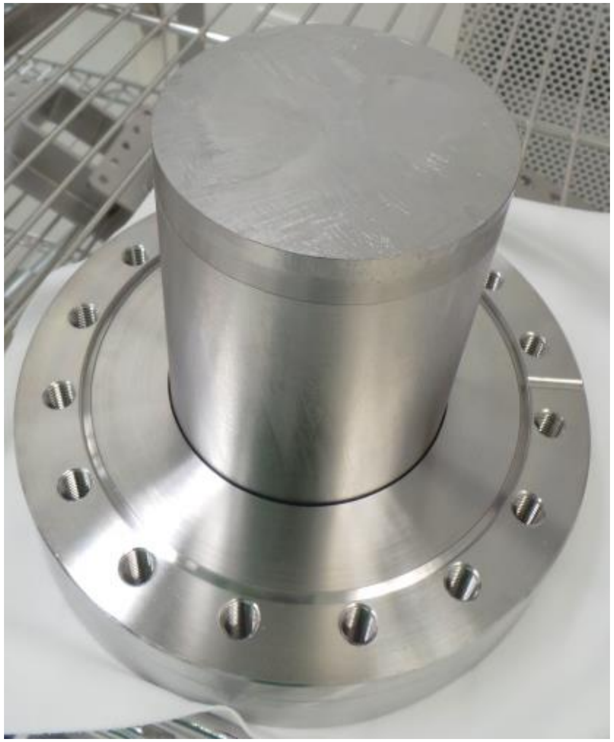
- Short sample holder for coating
  h = 12 mm
- Easier to handle
- No welding required
- Height adjustment possible
  → sensitivity on distance
  between rods and sample

Risks

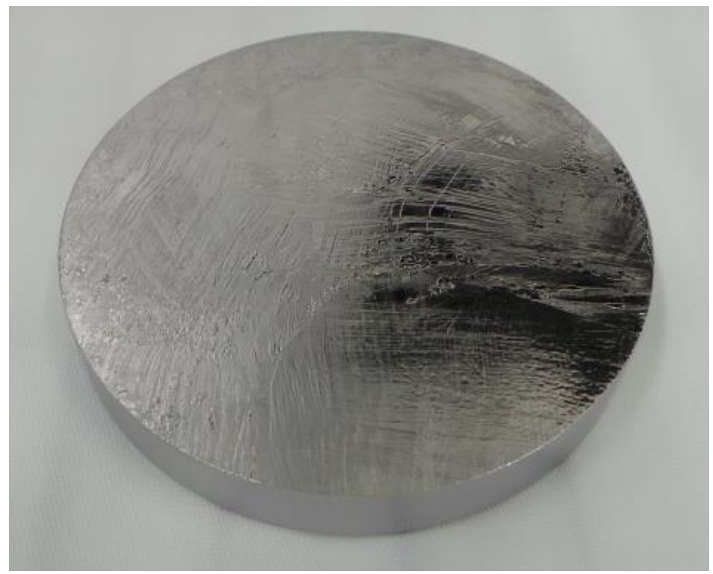
- Volumes of resonator and calorimetry chamber are connected
  - Cleanliness
  - Indium wire gaskets create additional risk: low quench field
- Thermal contact ?
- Impact on RF ?



Alternative calorimetry chamber I



- milled from large-grain bulk
- Nb RRR 300
- 150 µm chemical etch (BCP)
- Surface roughness
  - max: 10 µm peak-to-peak
  - typ: 2 µm

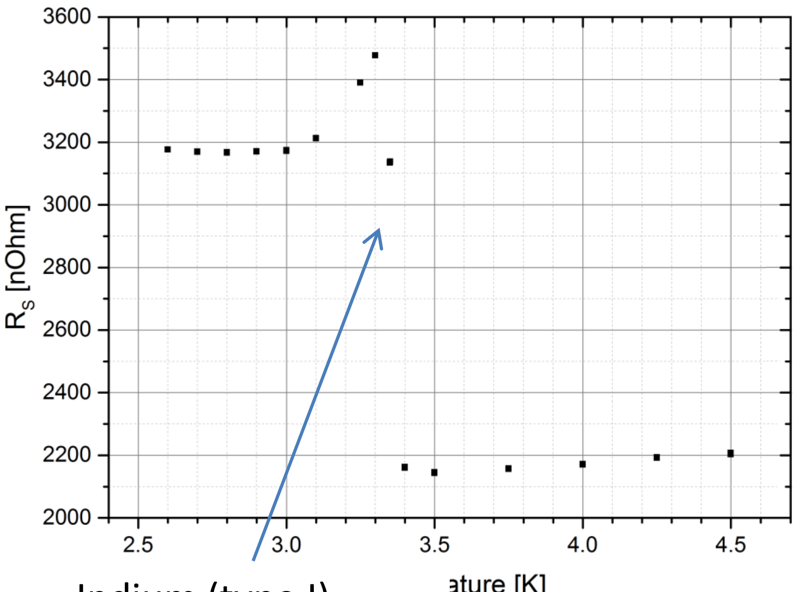


- baked at 850°C / 240 min
- 150 µm BCP

Surface resistance measurement

- First sample: with indium gasket
- (Too) high surface resistance
- Influence of indium at upper gasket visible
- Decrease of Rs at transition to nc Indium

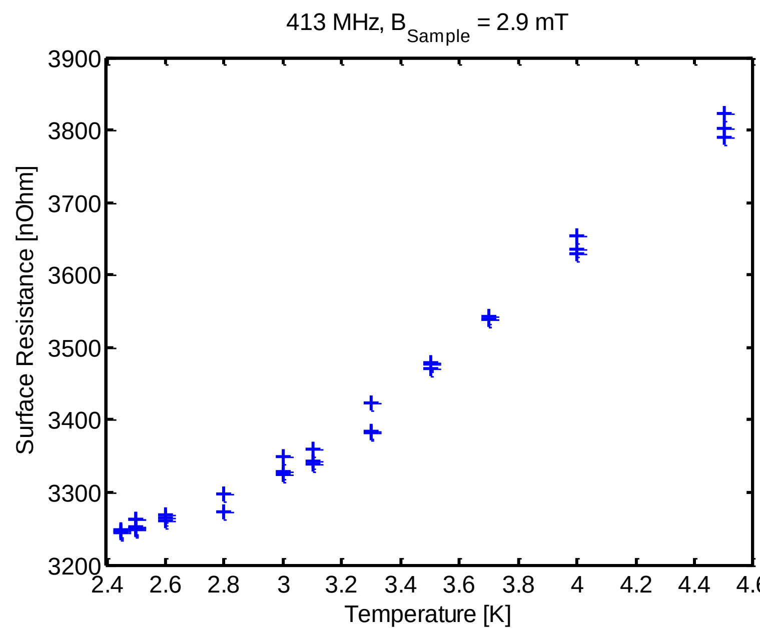
- Second sample: no indium
- 850 °C bake before BCP
- Indium peak gone
- Rs still too high



Indium (type I):

$T_c = 3.4\ \mathrm{K}$

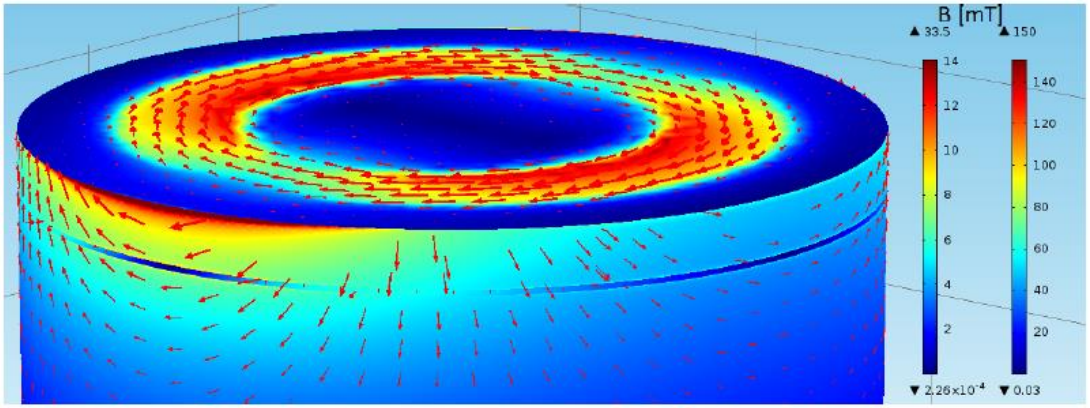
$B_c = 28.5\ \mathrm{mT}$

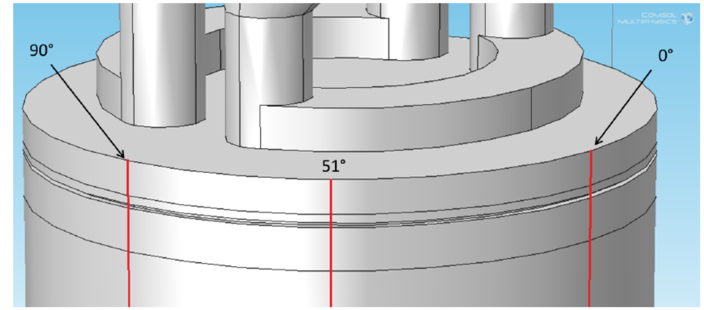


Possible causes ruled out

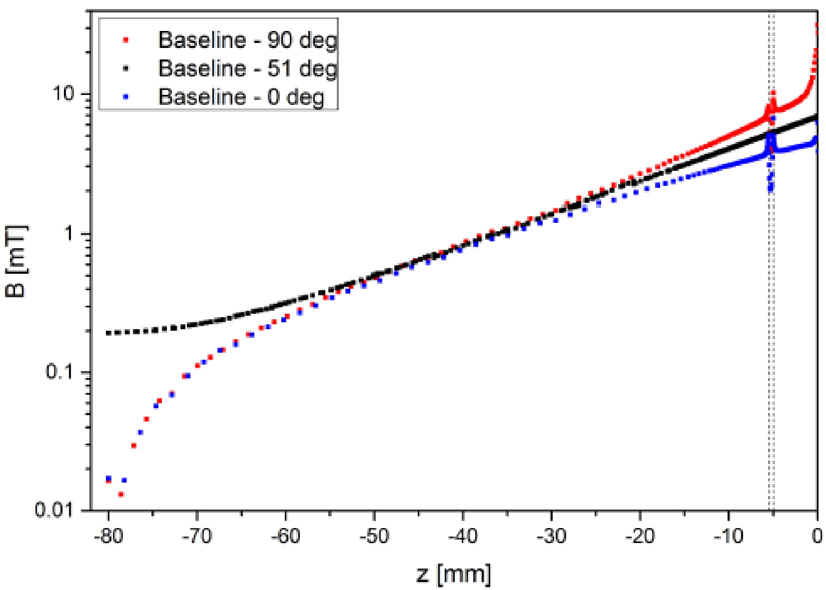
- Multipacting
  - possible electron paths too short
- Paschen discharge
  - pressure times distance value too low
- Resistivity change at superconducting transition of Indium
  - does not explain increased surface resistance after sc transition
- Discontinuous thermal conductivity of Indium at Tc (Indium)
  - does not explain increased surface resistance after sc transition
- B-Field enhancement at interface sample/cylinder
  - maximum conceivable enhanced field too low
- Local quench
  - should exhibit different temperature dependence of Rs
- Q-disease
  - sample baked after BCP
- Mechanical stress in sample (new manufacturer REUTER from a Heraeus ingot)
  - should have been relaxed upon 850°C bake
- Anisotropy of RF currents in gap

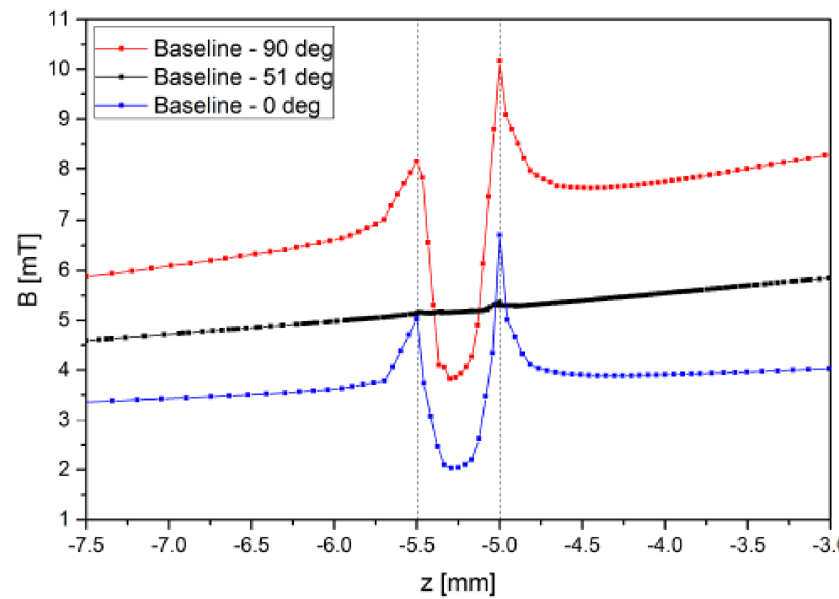
Simulations of the coaxial gap





RF currents passing Indium in gap vertically

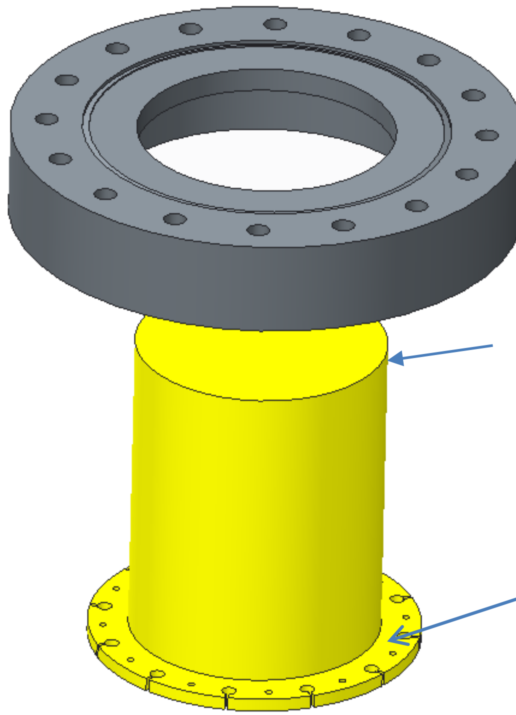


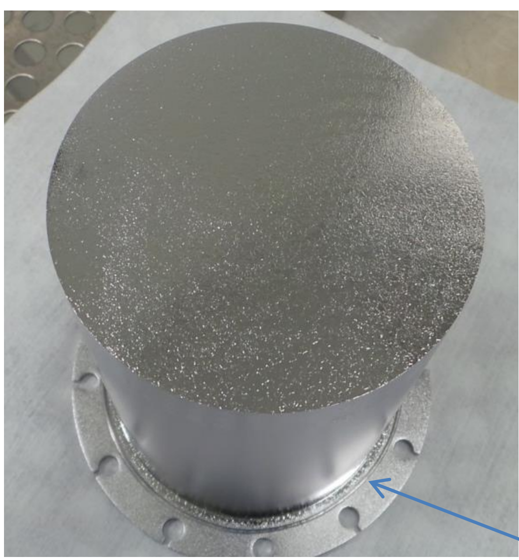


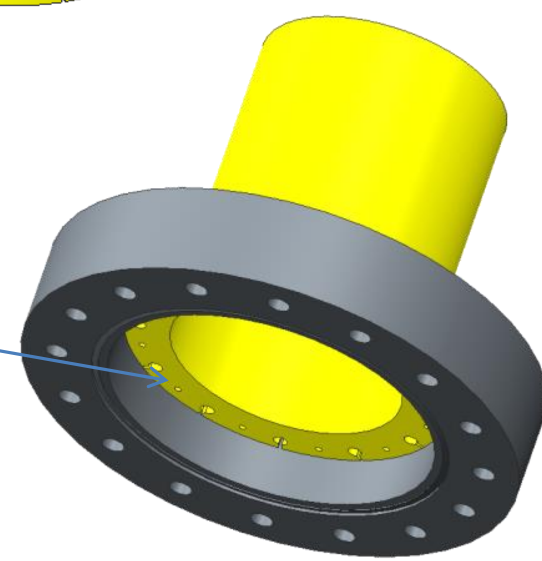
magnetic field in gap (150mT at sample)

Alternative calorimetry chamber II

- Pure Nb sample
  → high temperature treatments possible
  - Baking
  - N-doping
  - Diffusion coating (e.g. Nb_3Sn)
- UHV tight system
  → Indium wire gasket
- Height adjustment possible
- Short sample holder?
  → Electron beam welding required

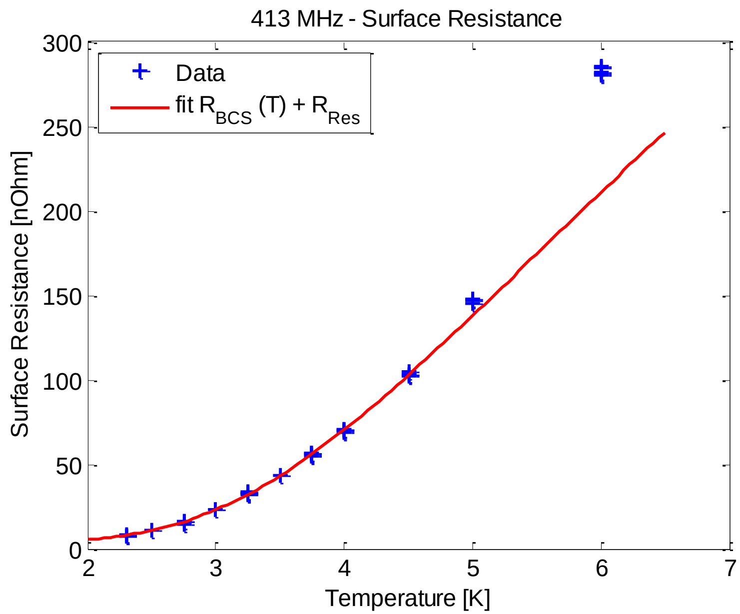


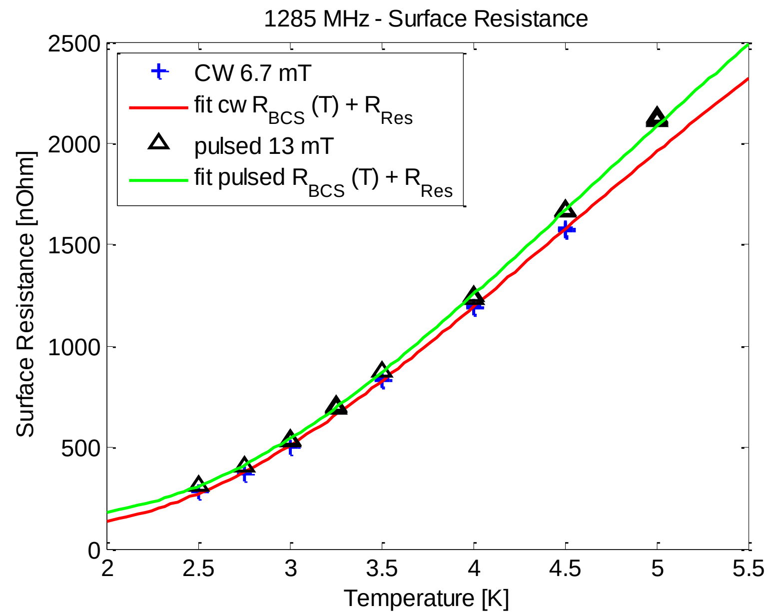




Surface resistance vs. Temperature

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



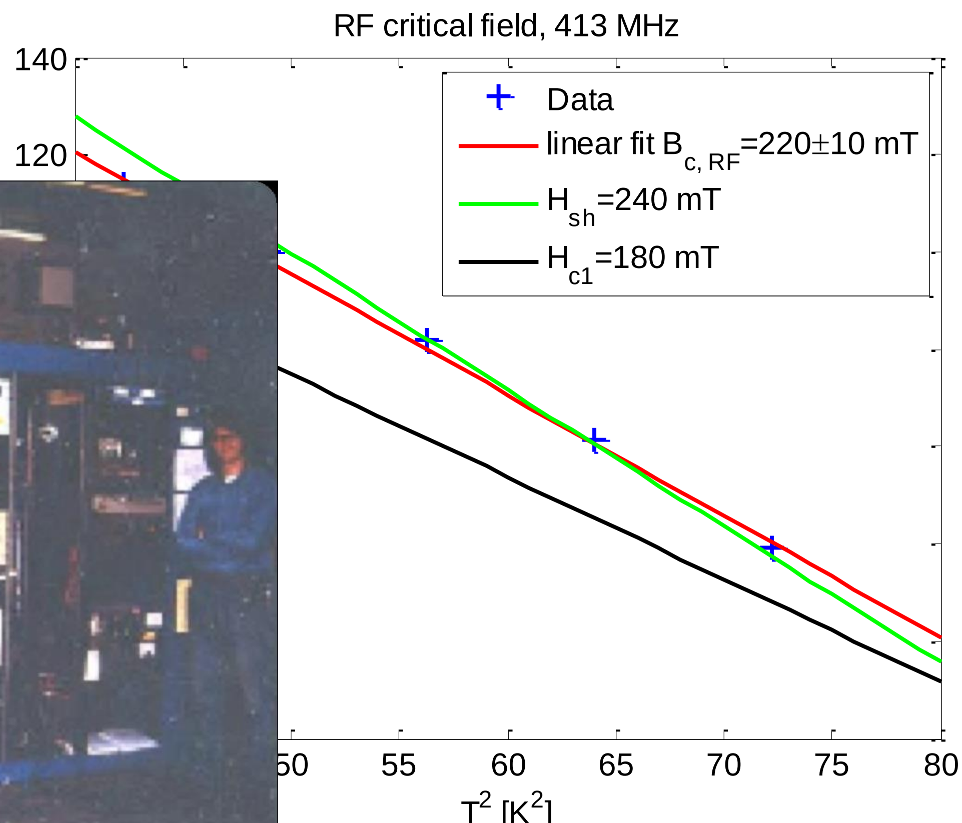


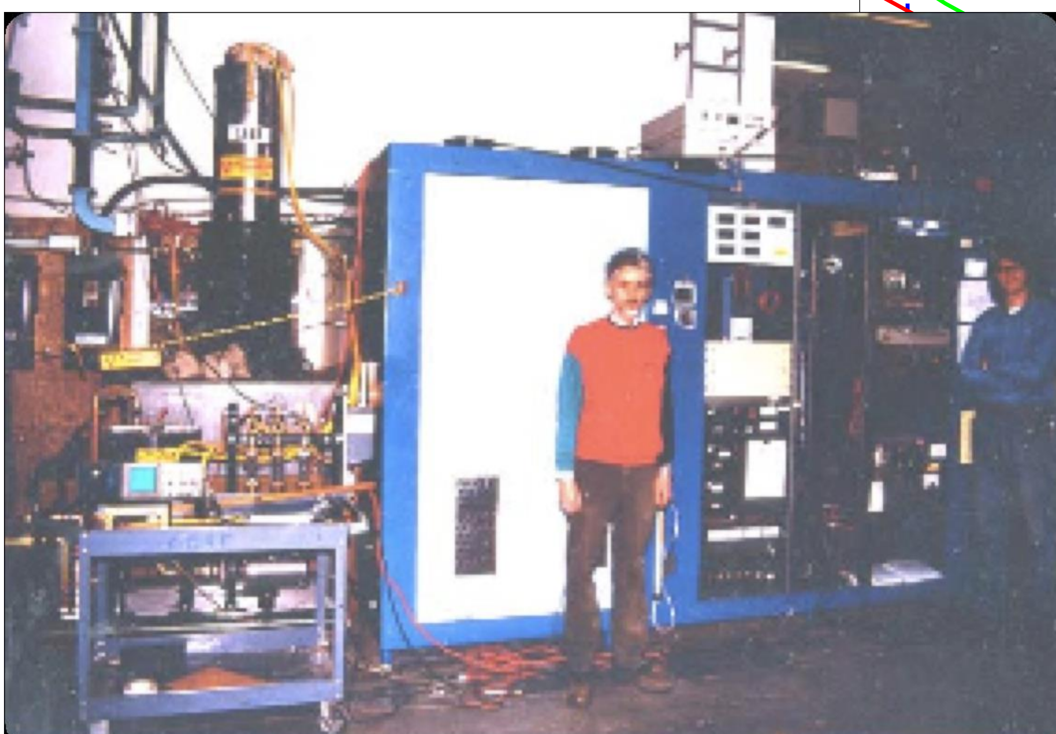
	413 MHz 16 mT, cw	1285 MHz 6.7 mT, cw	1285 MHz 13 mT, 30% DF
$A \left[\frac{\mu\Omega}{(\mathrm{GHz})^2\mathrm{K}}\right]$	4.1 ± 0.2	2.86 ± 0.13	3.37 ± 0.15
Δ [meV]	1.60 ± 0.02	1.29 ± 0.02	1.34 ± 0.02
R_{res} [nΩ]	4.3 ± 0.5	83 ± 12	136 ± 12

RF critical field

- Pulsed RF power with small duty factor (DF)
- Increase power until quench occurs
- $B_c(T) = B_{c,0} \cdot \left(1 - \left(\frac{T}{T_c}\right)^2\right)$

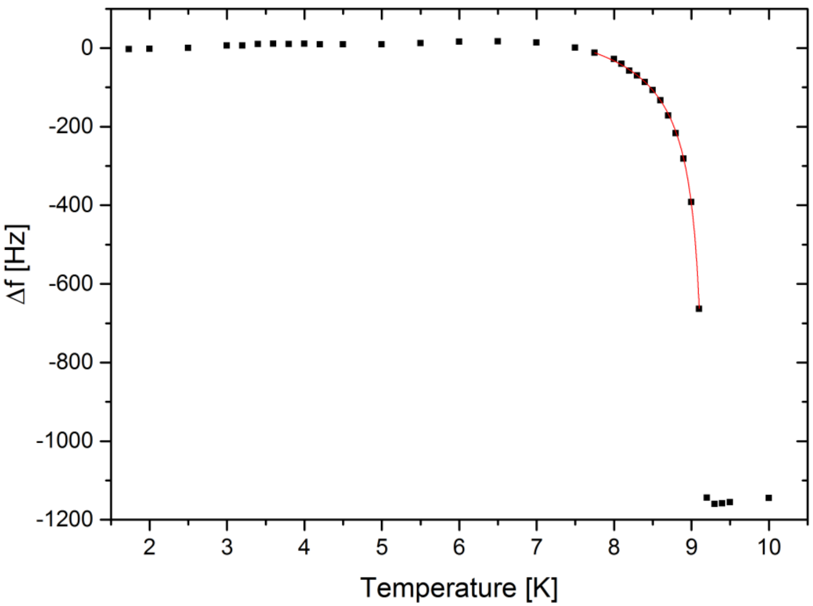
Cavity: 1 MW klystron,
3 years of work

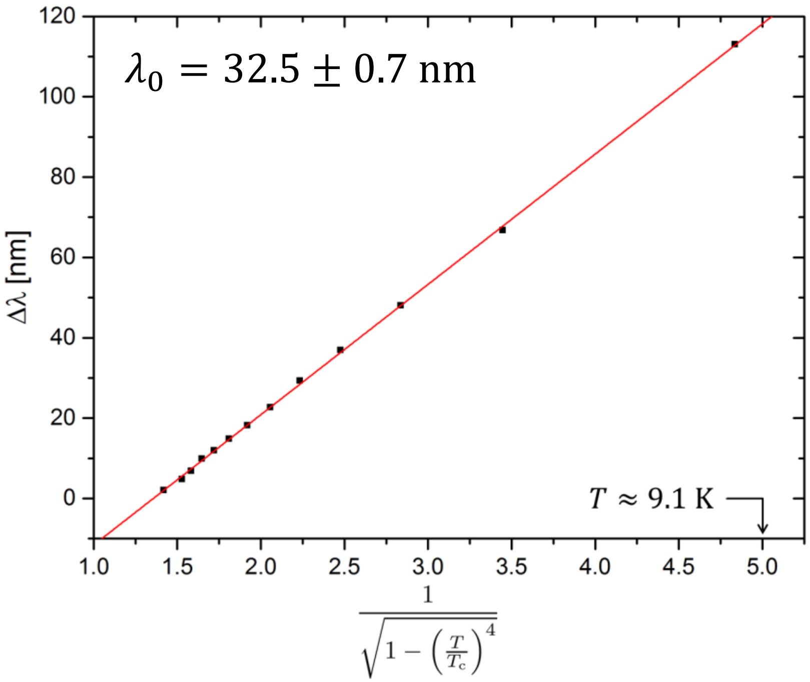




RF penetration depth

- Gorter-Casimir: $\lambda(T) = \frac{\lambda_0}{\sqrt{1-\left(\frac{T}{T_c}\right)^4}}$
- Slater´s Theorem and geometry factor of sample relate $\Delta\lambda = \lambda(T) - \lambda_0$ to Δf
- $\lambda(T = 0)$ from fit
  → electron mean free path l and RRR
- Value very close to $\lambda_L = 32\ \mathrm{nm}$





Summary & Outlook

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- QPR commissioned successfully
  - RF measurements up to 125 mT possible
  - Accuracy issues
- Simplified sample geometries investigated (ongoing)
  - Issues with Indium gasket
- Take part in followup projects:
  - ARIES (EuCARD3)
  - ANR-DFG proposal
  - EASITrain
- ToDo beyond Milestones and Deliverables:
  Test first non-Nb sample
  (if possible within last year of EuCARD2)

EuCARD2

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

CAPACITIES

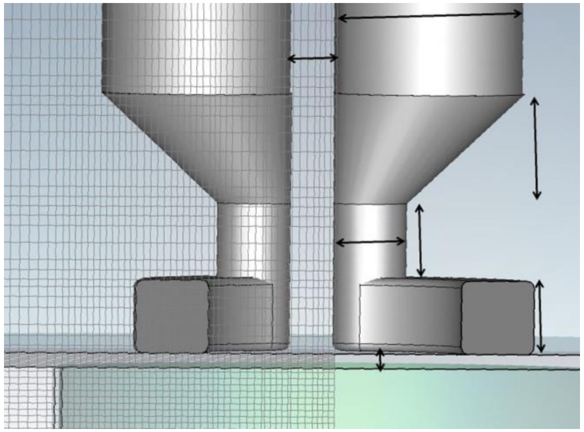
BACKUP SLIDES

Optimization of HZB design

- Optimization criteria
  - Phase space: Frequency, field strength, temperature
  - High resolution
- Full parameterization with CST
  - Maximizing figures of merit

	Baseline (CERN QPR)	Optimized
Operating frequencies	400 / 800 / 1200 MHz	433 / 866 / 1300 MHz (TESLA)
Focussing factor* $\frac{1}{U}\iint_{sample}\lvert H^2\rvert dA$	$5.15 * 10^7\ {}^{A^2}/_{J}$	$11.2 * 10^7\ {}^{A^2}/_{J}$
Risk of field emission B_{Sample}/E_{pk}	4.68 mT/(MV/m)	7.44 mT/(MV/m)
Operating range B_{Sample}/B_{Pk}	0.81	0.89
Microphonics 1st mechanical mode	69 Hz	172 Hz

* fraction of field exposure between sample and resonator

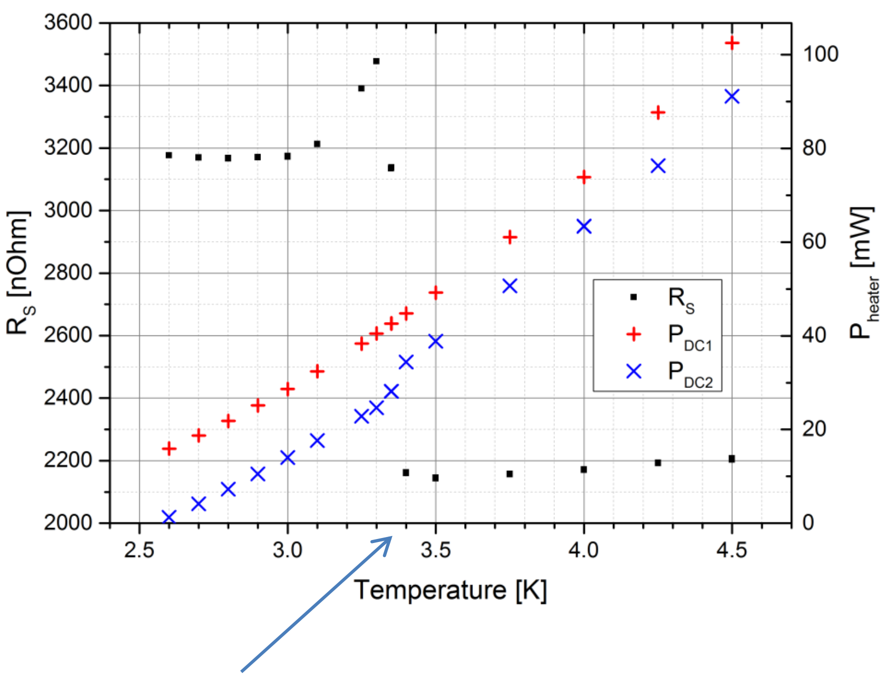


- Radius of rods increased 8 mm → 13 mm
- Gap reduced (pole shoes ↔ sample) 1 mm → 0.5 mm

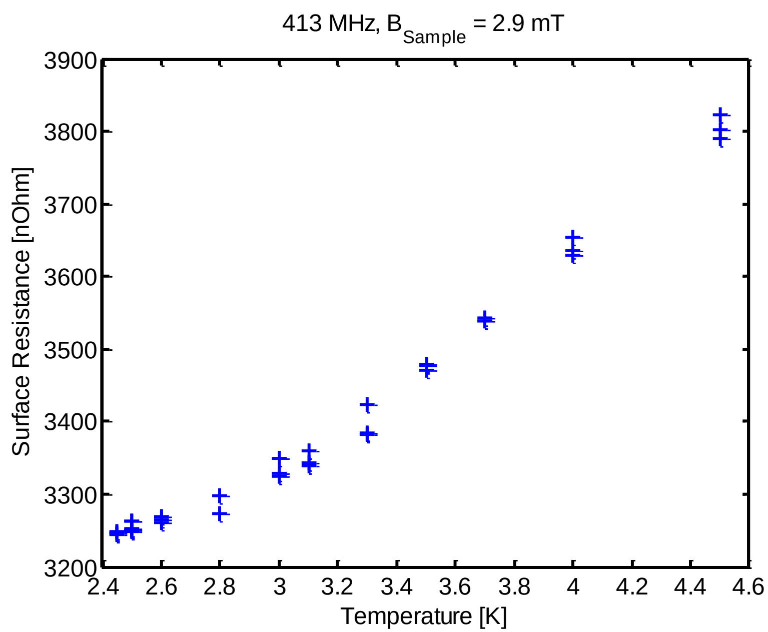
[R. Kleindienst, „Development of an Optimized Quadrupole Resonator at HZB“, SRF 2013]

- First sample: with indium gasket
- High surface resistance
- Influence of indium at upper gasket visible

- Second sample: no indium
- 850 °C bake before BCP



Indium: $T_c = 3.4$ K



RF penetration depth

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- $\frac{\Delta f}{f} = \frac{\frac{1}{4}\int_V^{V+\Delta V}\left(\epsilon_0|E|^2 - \mu_0|H|^2\right)\mathrm{d}V}{U}$
- Electric contribution negligible, $\mathrm{d}V = \mathrm{d}A\ \mathrm{d}\lambda$
- $\Delta\lambda = \lambda(T) - \lambda_0 = -\frac{G_{\mathrm{Sample}}}{\pi\mu_0 f^2}\Delta f$
- $\lambda_0(l) = \lambda_L\sqrt{1 + \frac{\pi\xi_0}{2l}}$ (Pippard)
- $RRR \approx \frac{l\ [\mathrm{nm}]}{2.7}$