Measurement of Surface Resistance Properties with Coaxial Resonators – Review

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Acknowledgement

- This research is funded by a NSF grant provided to Center for Accelerator Science at Old Dominion University.
- This talk is enriched by the research results using QWR at TRIUMF (P. Kolb, R. E. Laxdal).

  See poster TUP046 for more details.
- This research has tremendously benefitted from support of Jefferson Lab SRF Institute’s all staffs and state of art facility.
- The research is my Ph.D. thesis project with my advisor Dr. Jean R. Delayen.
- Past research has provided inspiration and valuable guidelines.

Outline

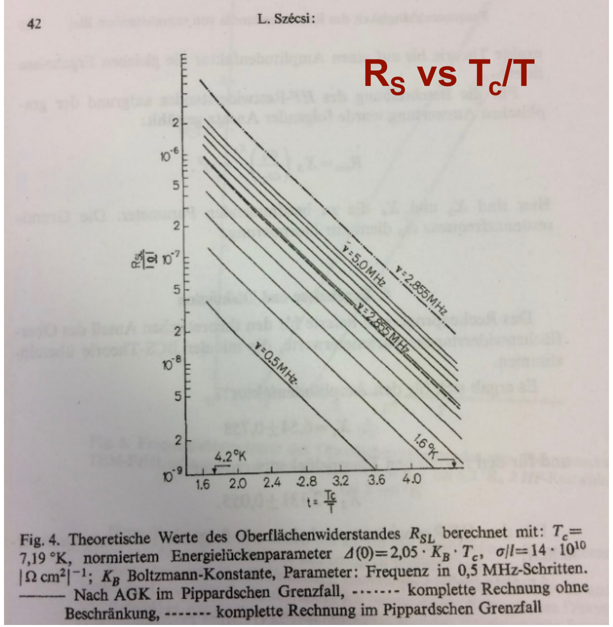
- Motivation and goal
- Brief history and multimode resonator design
- Cavity preparation
- Test methodology
- Test results
- Data analysis
- Summary and plan

Motivation and Goal

- The research consists of experimental and theoretical parts to address the unresolved issues of the surface resistance of superconductors at high rf field, and in particular how the surface composition and structure can be modified and tuned in order to reduce surface resistance.
- Understanding of the surface resistance of superconductors (Niobium) requires a systematic approach with well controlled parameters. Extracting frequency, temperature, field dependence is the best approach to understand the physics behind loss mechanisms.
- Testing the same surface at different frequencies is the main advantage of using multimode cavities such as HWR and QWR.

Brief History

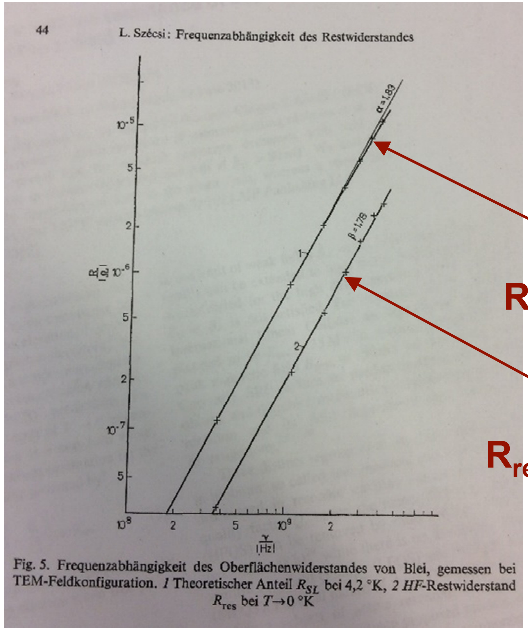
- L. Szécsi in 1970 – “Measurement of the dependence on frequency of the residual resistance of superconducting layers of lead”
- Measured 375 MHz to 5000 MHz using Half-Wave Coaxial cavity.



42 L. Szécsi:

R_S vs T_c/T

Fig. 4. Theoretische Werte des Oberflächenwiderstandes R_{SL} berechnet mit: $T_c=7{,}19\,°K$, normiertem Energielückenparameter $\Delta(0)=2{,}05\cdot K_B\cdot T_c$, $\sigma/l=14\cdot 10^{10}\,|\Omega\,\mathrm{cm}^2|^{-1}$; K_B Boltzmann-Konstante, Parameter: Frequenz in 0,5 MHz-Schritten. ——— Nach AGK im Pippardschen Grenzfall, ------- komplette Rechnung ohne Beschränkung, ------- komplette Rechnung im Pippardschen Grenzfall



44 L. Szécsi: Frequenzabhängigkeit des Restwiderstandes

Fig. 5. Frequenzabhängigkeit des Oberflächenwiderstandes von Blei, gemessen bei TEM-Feldkonfiguration. *1* Theoretischer Anteil R_{SL} bei 4,2 °K, *2 HF*-Restwiderstand R_{res} bei $T\rightarrow 0\,°K$

T=4.2K

$R_{BCS} \propto \omega^{1.83}$

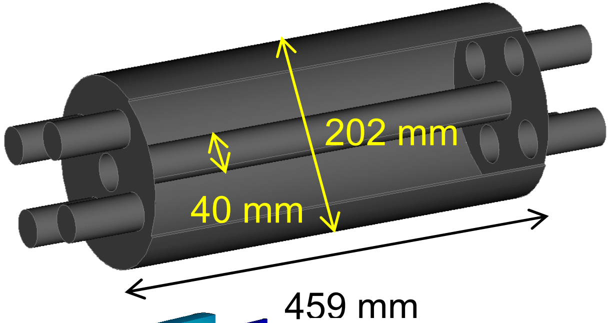
T→0K

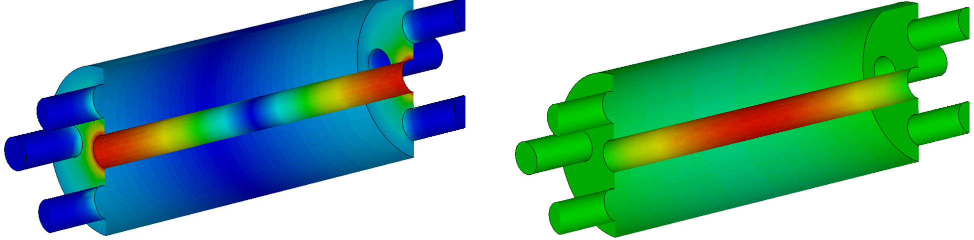
$R_{res} \propto \omega^{1.78}$

https://link.springer.com/article/10.1007%2FBF01394760

Design of Half Wave Coaxial Cavity

- Cavity design to provide range of frequencies of particular interest to accelerators.
- These TEM modes sufficiently separated by other TM and TE modes.
- Aim to achieve high rf surface field and free of multipacting.





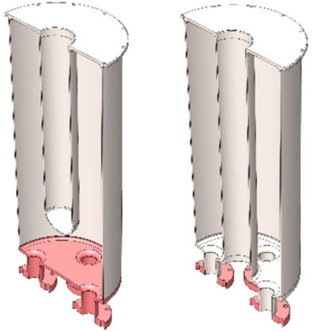
Surface magnetic field (left) and electric field of TEM1 mode

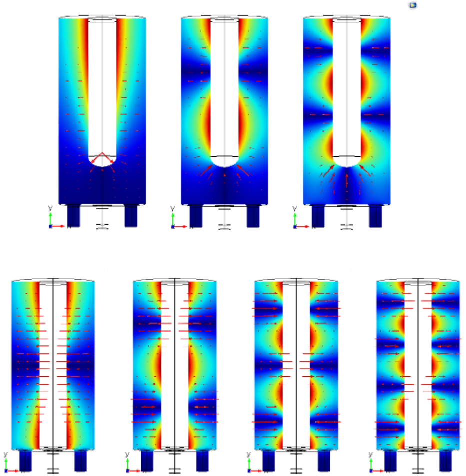
Mode	f (MHz)	G (Ohm)
TEM1	325.4	59
TEM2	650.8	119
TE111	869.6	
TEM3	976.1	179
TE112	1034.9	
TE113	1265.4	
TEM4	1301.3	239
TE211	1470.1	

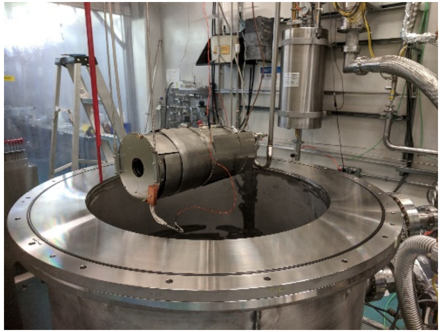
TRIUMF Coaxial Test Cavities

Philipp Kolb – TRIUMF

- Designed and build two coax cavities, QWR and HWR, with a similar purpose & size as a 1.3GHz single cell cavity.
- To study frequency dependence of treatments independent of external factors such as surface roughness, cooldown speed, external magnetic field….
- No beam ports on cavity, simplifying geometry.
- RRR grade Nb for cavity walls, reactor grade for ports/bottom plate (QWR). No NbTi/SS -> less sources of contamination.







More details at poster/paper

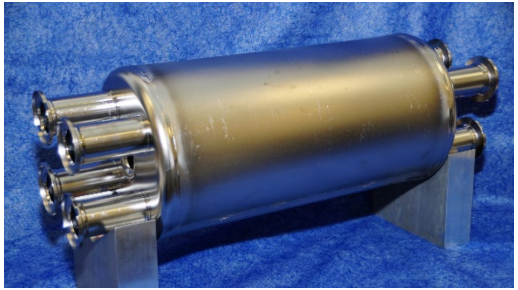
TUP046

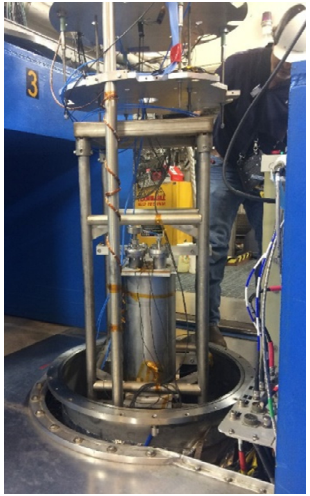
QWR	Simu. /MHz	Meas. /MHz
TEM	217	217.4
TEM	647	647.3
TE111	892	–
TEM	1055	1054.2
TE112	1103	1100.8/1103.5

HWR	Simu. /MHz	Meas. /MHz
TEM	389	388.6
TEM	778	777.4
TE111	905	901.9/906.6
TE112	1128	1125.4/1129.1
TEM	1166	1166.1
TE113	1424	1421.9/1424.8
TEM	1555	1554.8
TE211	1602	1600.7

Cavity Preparation

- Prepare cavity per typical process
  - Bulk BCP 200 microns
  - Heat treatment 800 C 3 hours (TRIUMF 6 hours)
  - Light BCP 20 microns
  - HPR
  - Cleanroom assembly
  - Evacuation, leak check
  - Fast cool down to 4.3K
- Baseline test
- Bake 120 C 6 hours (TRIUMF 48 hours), cavities not opened
- Test

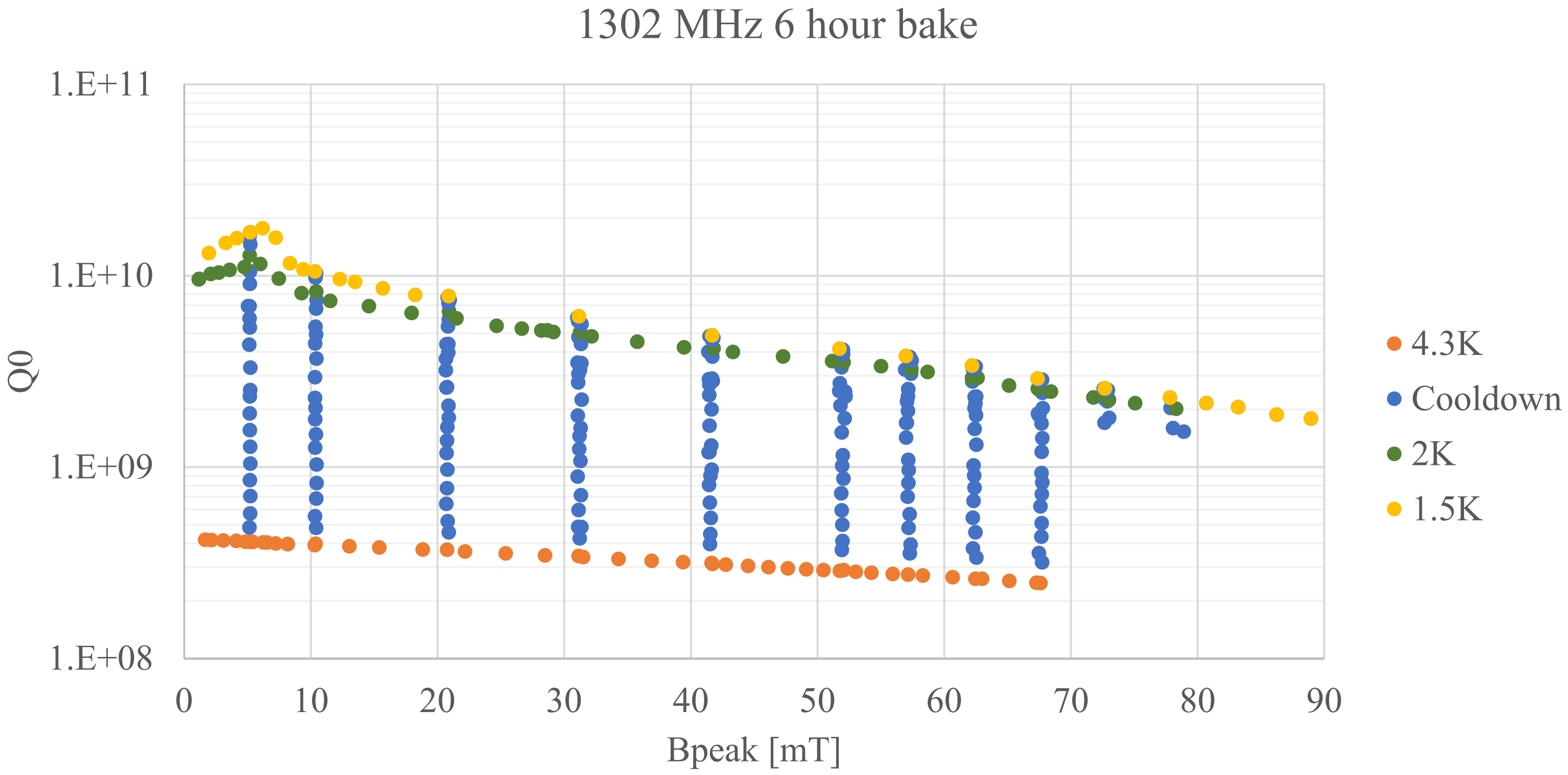




Test Methodology

- Controlled cool-down from room temperature to 4.3K (this time as fast as possible to minimize trapped flux)
- System calibration
- Multipacting processing if necessary
- Fine step Q measurement at 4.3K
- Slow cooldown to 2K (4.3K→1.5K 6 hours)
  - Power measurement (Q-curves) at fixed set of field levels as temperature decreases.
- Fine step Q measurement at 2K
- Further measurement down to 1.5K.
- Cable calibration (to compare the initial calibration)
- Warm up to 4.3K
- Repeat next frequency (start with 325 MHz and in order)

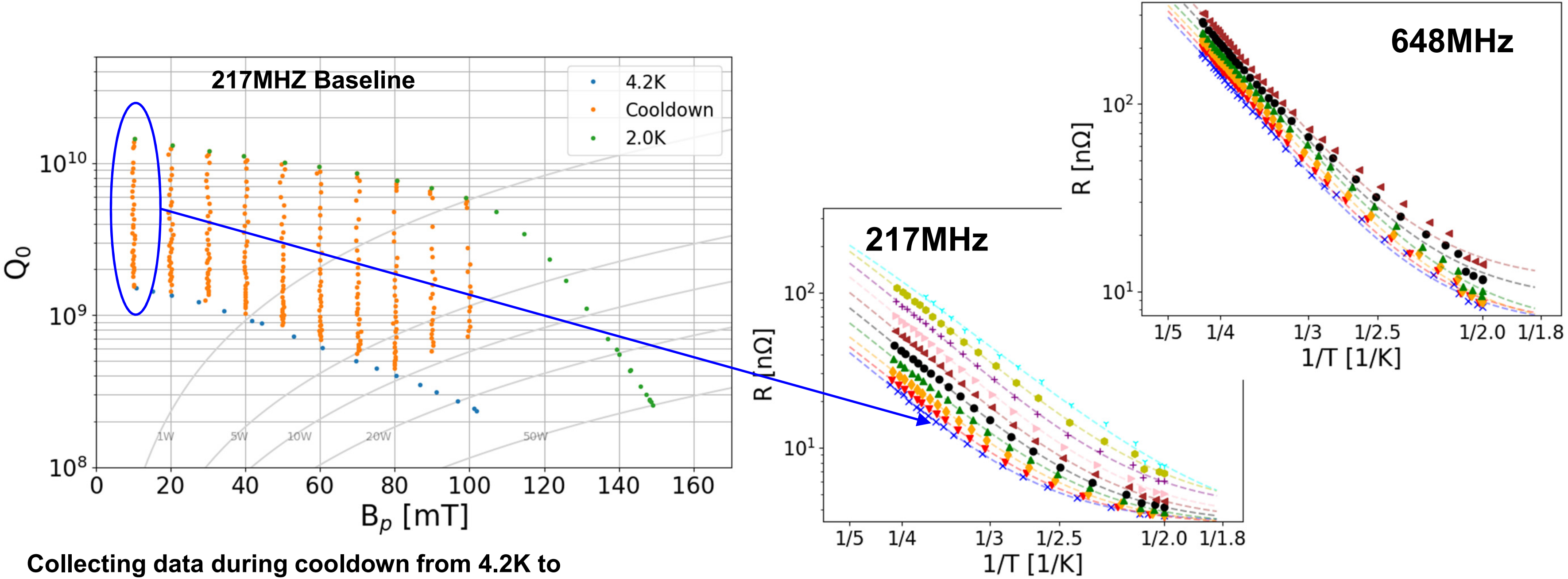
Q(Power) Measurements



Data Processing

- Extract average R_s from geometric factor for series of fixed B_p.
- Perform fit to $R_s = \frac{A}{T}\exp\left(-\frac{D}{T}\right) + R_{res}$ for series of B_p.
  - find $A(B_p)$, $D(B_p)$, $R_{res}(B_p)$ for a given frequency.
  - extract average $R_s(B_p)$ for any fixed bath T.
- Extract real $R_s(B_p)$ for any fixed bath T.
- Repeat for each frequency.
- Find frequency dependence.
  - find $A(B_p, \omega)$, $D(B_p, \omega)$, $R_{res}(B_p, \omega)$.
- Correction for bath temp. vs internal surface temp if needed.

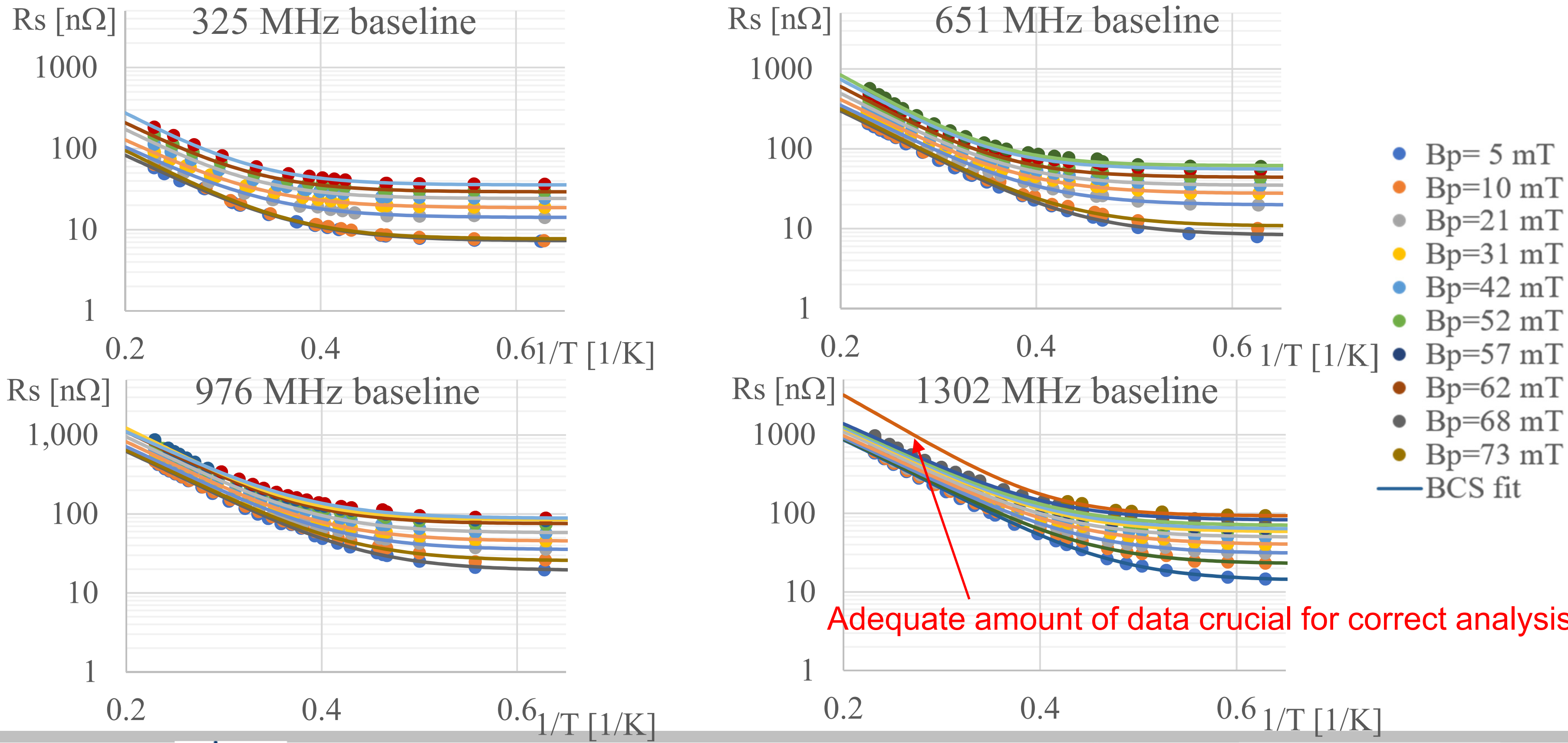
Data collection and Fitting (QWR)



Collecting data during cooldown from 4.2K to 2.0K at fixed gradients.
Conversion of Q -> Rs with field independent geometric factor G.

$$R_s(B,T) = \frac{A(B)}{T}\exp\left(-\frac{C(B)}{T}\right) + R_{res}(B)$$

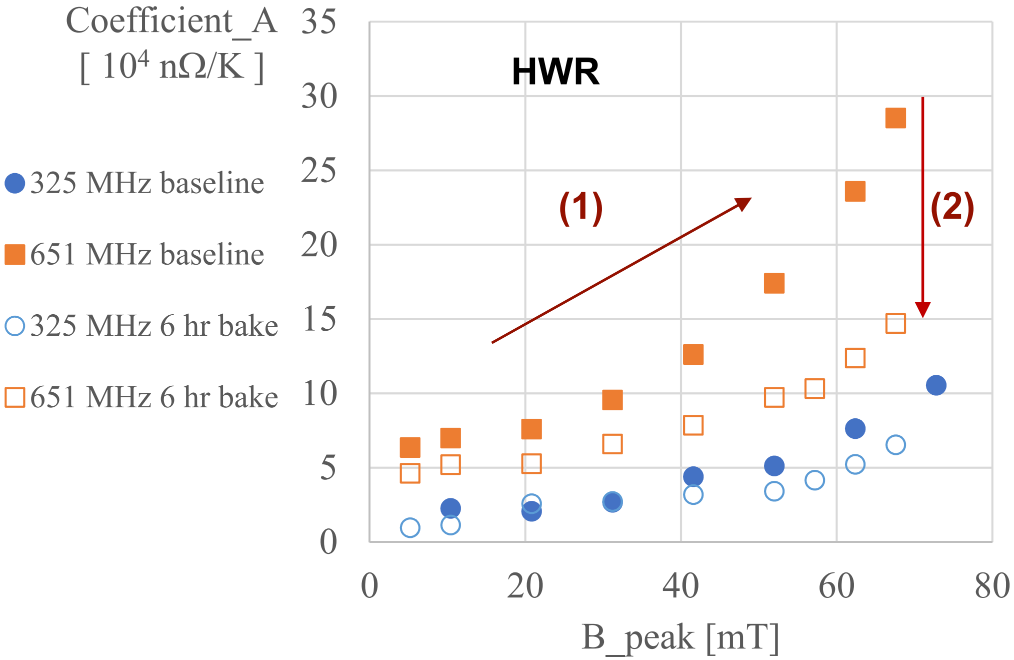
Test Results – $R_s(T)$

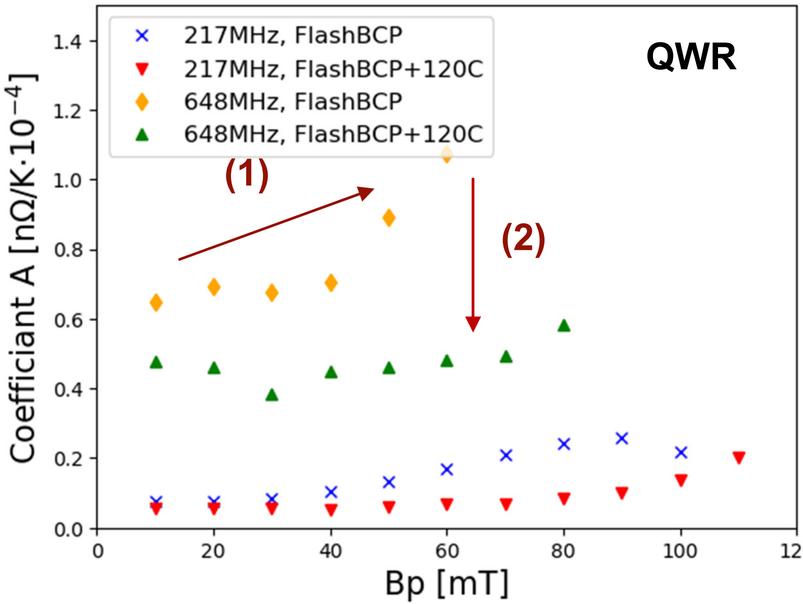


Adequate amount of data crucial for correct analysis.

$A(B_{peak})$

$$R_s = \frac{A}{T}\exp\left(-\frac{D}{T}\right) + R_{res}$$

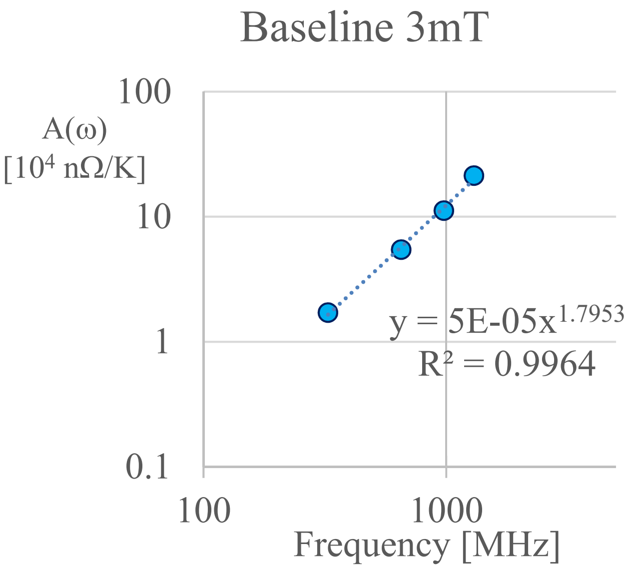


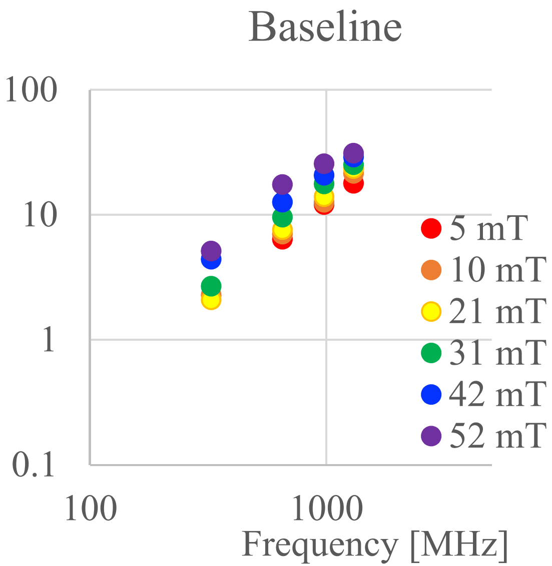


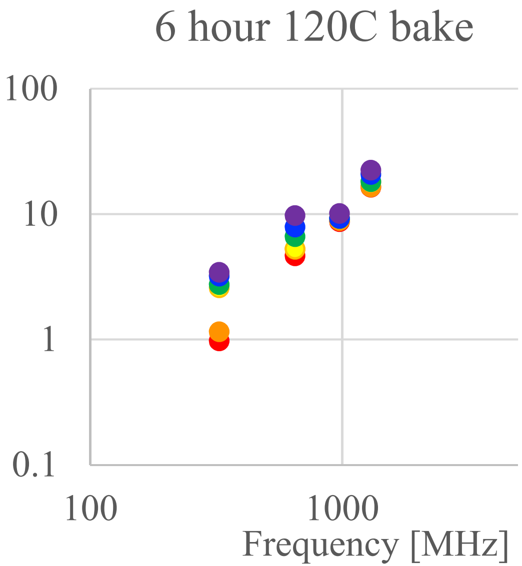
1) Results show field dependence of A.
2) 120 C bake lowers BCS resistance.

A(ω)

$$R_s = \frac{\boldsymbol{A}}{T}\exp\left(-\frac{D}{T}\right) + R_{res}$$


Baseline 3mT

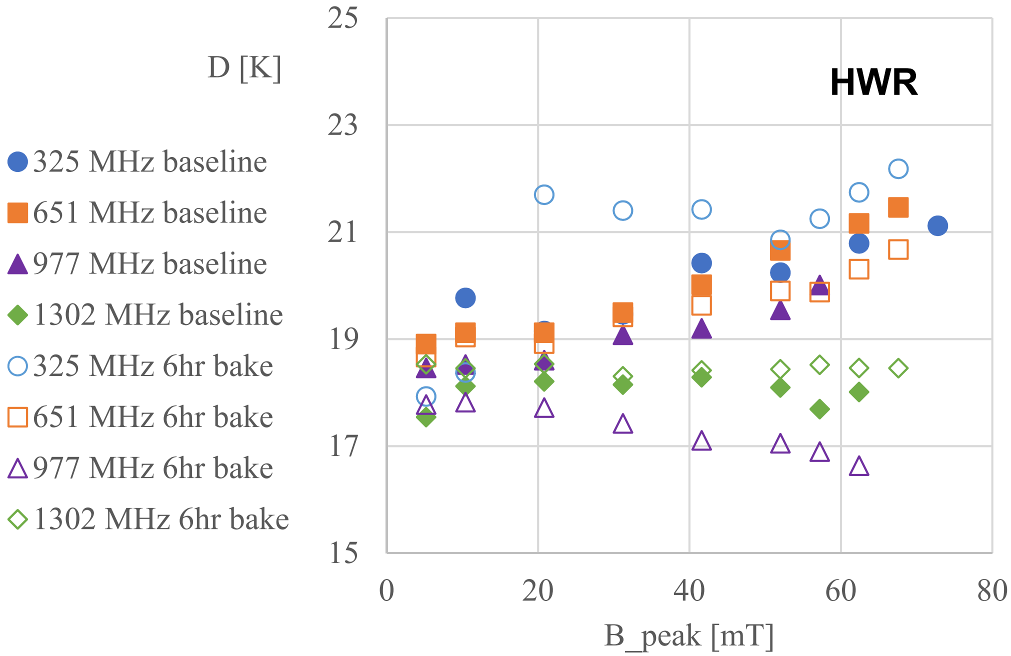

Baseline

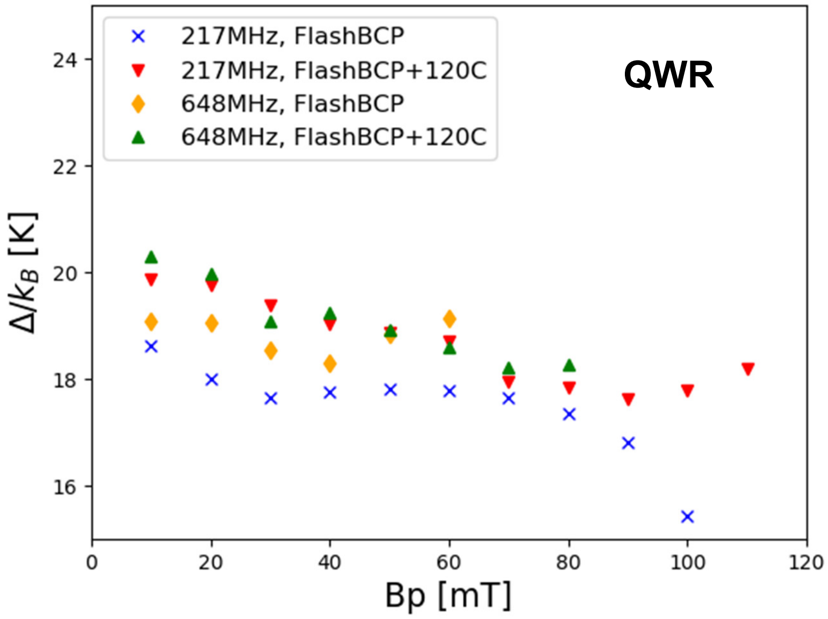

6 hour 120C bake

- Data points measured at low field show the frequency dependence $R_{BCS} \propto \omega^{\sim 1.8}$.
- Frequency dependence (slope) seems to decrease at higher frequencies.
- After bake, as field increases frequency dependence decreases.

$D(B_{peak}, \omega)$

$$R_s = \frac{A}{T}\exp\left(-\frac{D}{T}\right) + R_{res}$$

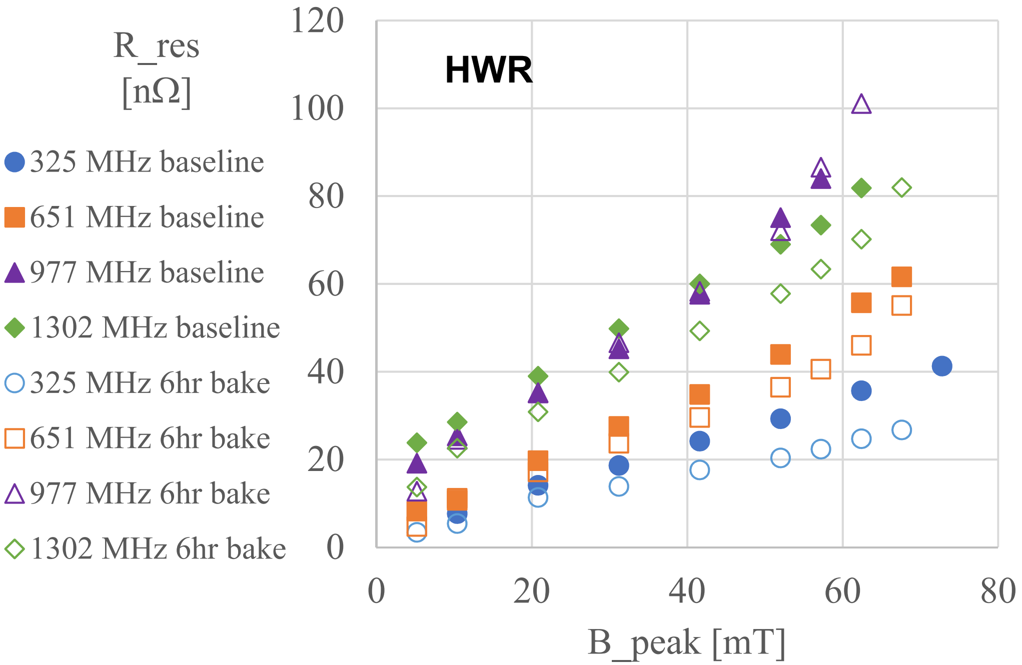


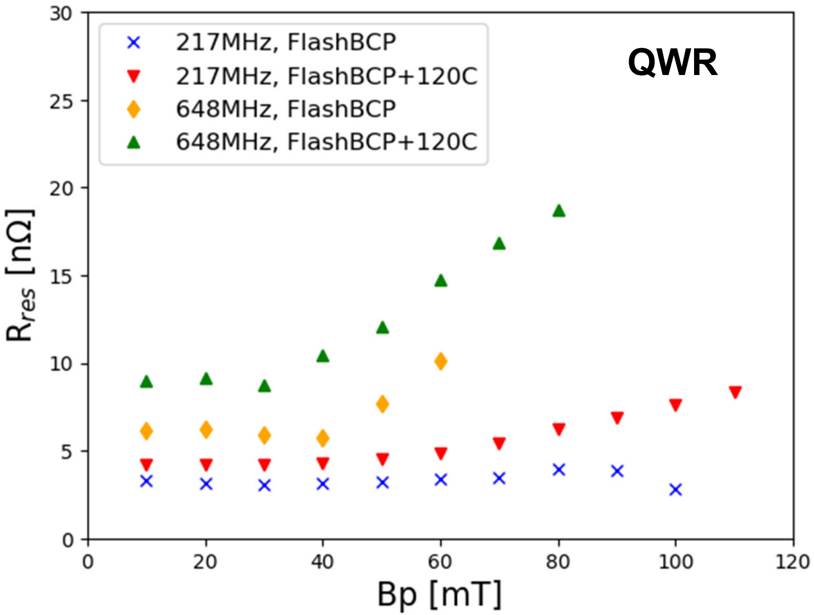


- D appears little dependence over field and frequency.

$R_{res}(B_p)$

$$R_s = \frac{A}{T}\exp\left(-\frac{D}{T}\right) + \boldsymbol{R_{res}}$$

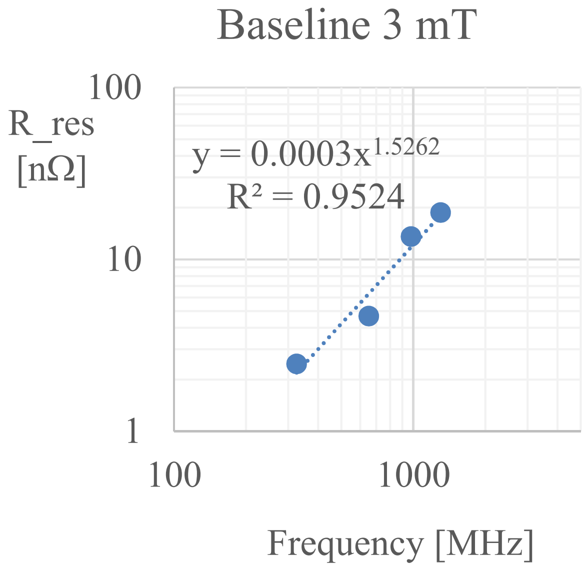


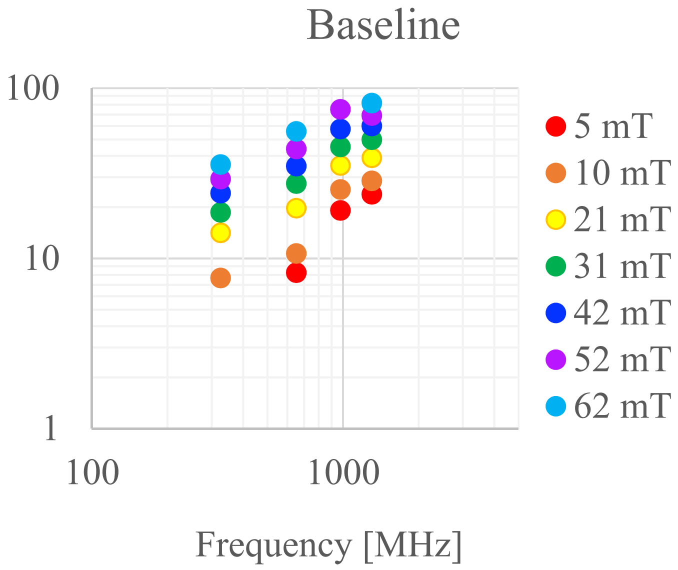


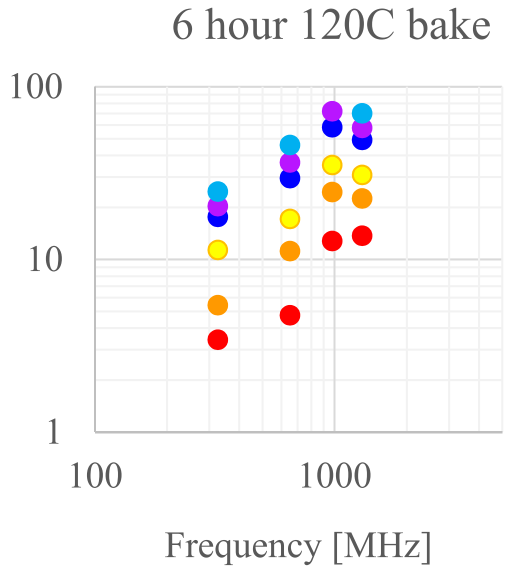
- Appears linear field dependence of residual surface resistance.
- Bake effect on R_{res} different for ODU HWR and TRIUMF QWR. (Difference in bake time???)

$R_{res}(\omega)$

$$R_s = \frac{A}{T}\exp\left(-\frac{D}{T}\right) + \boldsymbol{R_{res}}$$







- At low field, $R_{res} \propto \omega^{\sim 1.5}$.
- It appears the frequency dependence (slope) decreases as the field increases.
- Effect of trapped vortices is subject of further investigation.

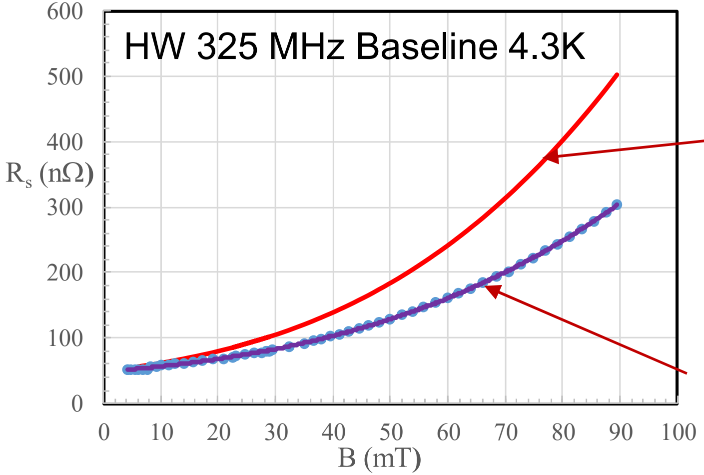
Extracting Real R_s

- At ODU, we developed a procedure to calculate real R_s.

Determination of the magnetic field dependence of the surface resistance of superconductors from cavity tests

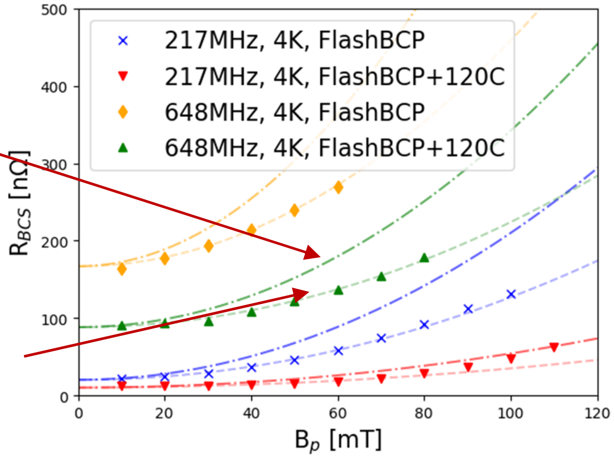
J. R. Delayen, H. Park, S. U. De Silva, G. Ciovati, and Z. Li

Phys. Rev. Accel. Beams 21, 122001 – Published 5 December 2018



R_s

Data and fit of $\overline{R_s}$



Observations to Date

$$R_s = \frac{\boldsymbol{A}}{T}\exp\left(-\frac{\boldsymbol{D}}{T}\right) + \boldsymbol{R_{res}}$$

- Results are preliminary.
- Frequency dependence of $\boldsymbol{A}$ – close to $\omega^{1.8\text{-}2}$ at low field as BCS theory predicts, weaker dependence at higher field observed.
- Field dependence of $\boldsymbol{A}$ – seems stronger dependency at higher frequency.
- $\boldsymbol{D}$ appears to be frequency independent and weakly field dependent.
- Frequency dependence of R_{res} - decreases as field increases.
- Baking decreases R_{BCS} but effect on R_{res} needs further investigation.

Lesson Learned

- Both HW-coax cavity at ODU and QWR at TRIUMF are limited in maximum surface field due to insufficient cooling of the center conductor.
  - Size of inner conductor will be increased for next ODU cavity (HW-coax 3).
  - TRIUMF changed test setup to improve the cooling.
- Localized defects make the interpretation of data analysis difficult since it is based on the assumption of uniform surface property.
- For the same reason, cavities should operate in the regime where they are free of multipacting and field emission.

Future Exploration

- In short term, ODU will repeat the experiments with 2nd HW-coaxial cavity and TRIUMF is starting test with HW-coax cavity (389-1555 MHz).
  - TRIUMF's QWR fairly advanced in treatments, N2 infusion soon.
  - ODU is building 3rd cavity. (325-1300 MHz)
- Main goal of the long term program is to understand the origin of nonlinear loss mechanisms and how to improve the cavity performance.
  - Low temperature baking
  - Nitrogen doping/infusion
  - Flux expulsion study
  - Electropolishing
  - High temperature heat treatment
- Another goal is to explore new srf materials. (Nb3Sn coating, NbTi, MgB2 …)

Final Message

- Studies on Rs with multimode cavities show great potential to understand all the contributions to the power dissipation in superconductors at rf frequencies of interest.
- Underlying assumption is that the surface is uniform in rf properties.
  - Surface field distribution is almost identical for all TEM modes of HWR and QWR, (much better than other type of cavities) but not exactly so.
  - It is a source of errors in addition to the measurement errors.
- Wide range of data collection is absolutely necessary for correct analysis.
  - Since we do not yet have full control of all parameters, results contain randomness and no final conclusion should be drawn based on limited set of data.
  - It is advisable to repeat the same experiment preferably in different institutions.