TRIUMF

HWR/QWR Test Data

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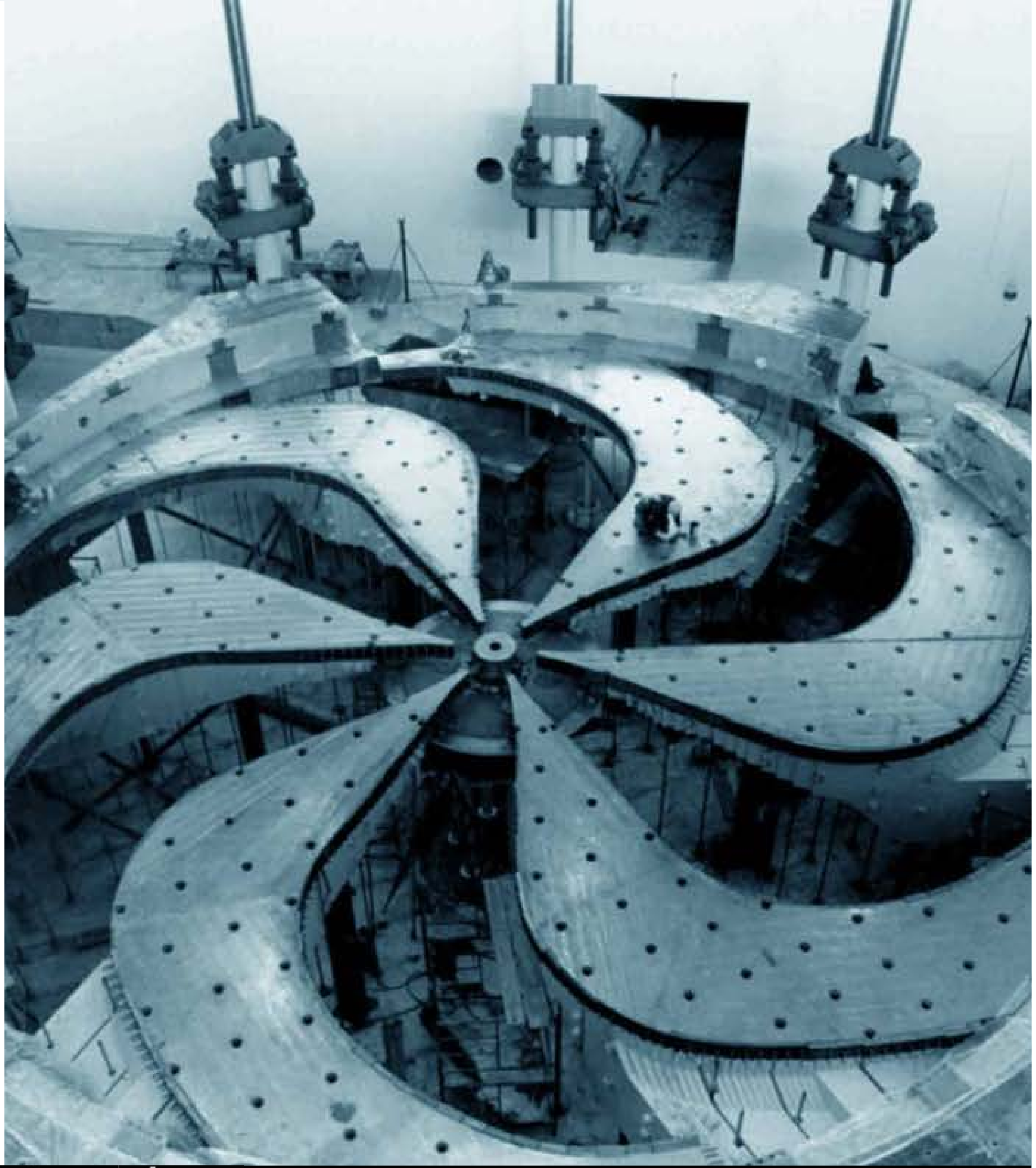
TRIUMF

June 26, 2018



Discovery, accelerated

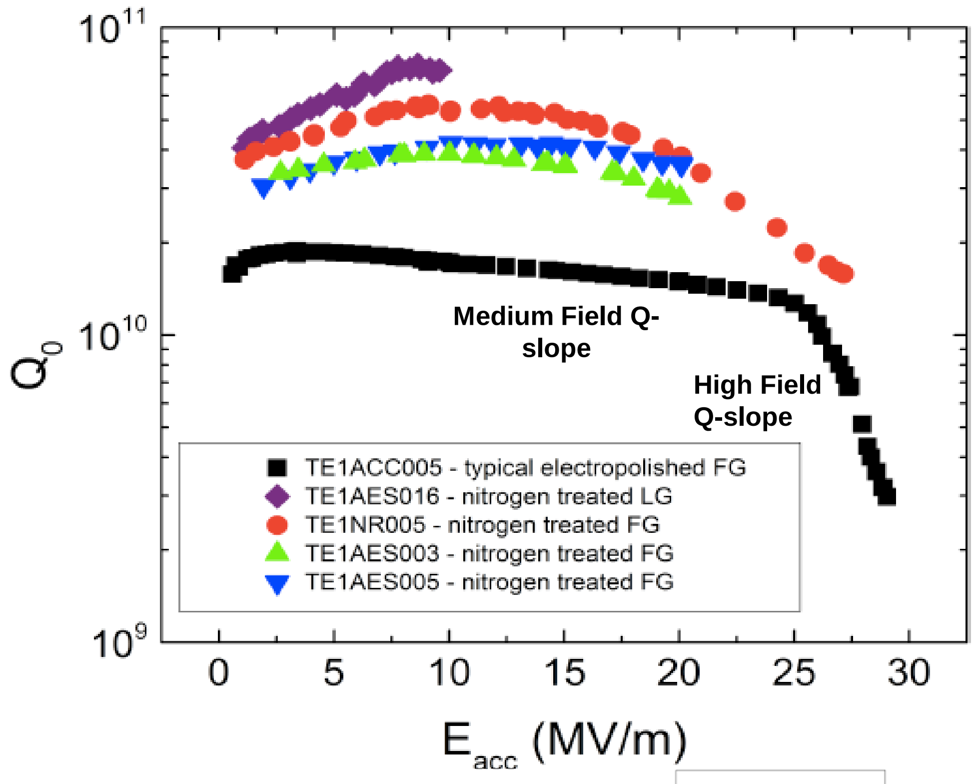
Outline

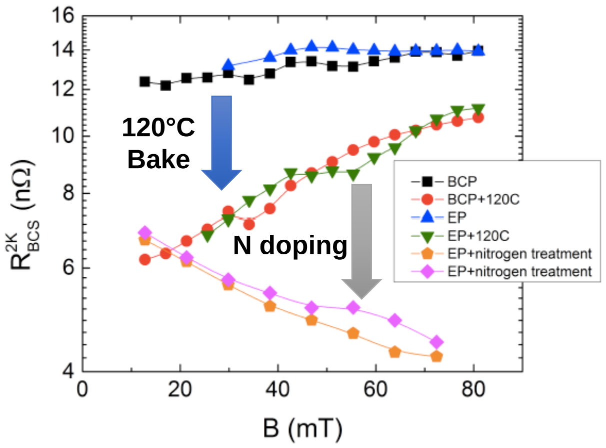
- Introduction
- Separation of Rs and Rbcs
- QWR and HWR for RISP
- Comparing Rs (B) across different geometries
- High performance – a data point

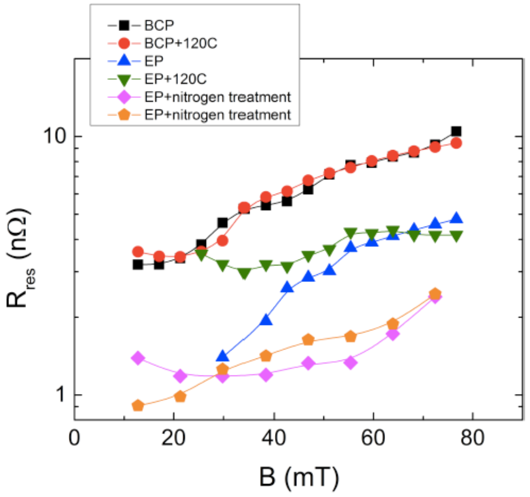
1.3GHz Development

- Optimizing and understanding RF performance has focused primarily on 1.3GHz cavities.
- High gradient studies for ILC
- High Q studies for LCLS-II.
  - N doping enhanced low field Q-slop, and increased Q in medium field.
  - Recipe is being optimized for higher quench field
- Separating R_{res} and R_{BCS} is also instructive in low beta (low frequency) cavities to provide an insight to the mechanisms at play.

A. Grassellino, et al., 'Nitrogen and Argon Doping of Niobium for Superconducting Radioactive Cavities: a Pathway to Highly Efficient Accelerating Structures', arXiv:1306.0288, July 2013.



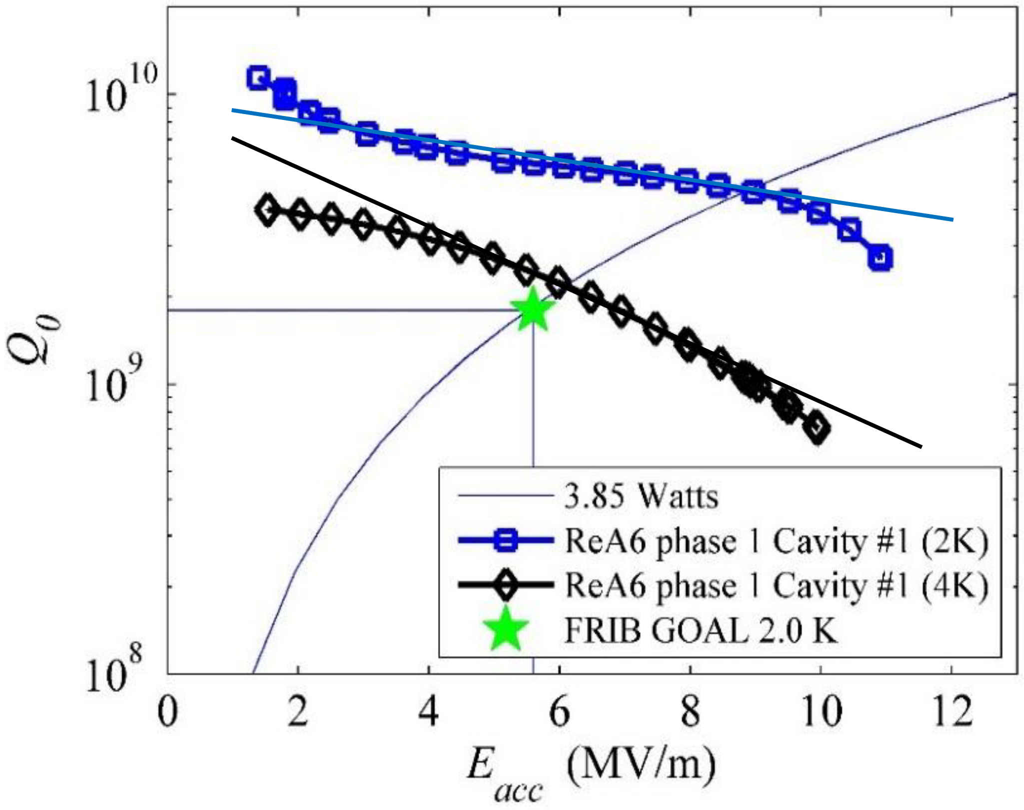




Low Beta Resonators

- Due to R_{BCS} frequency dependence low frequency resonators can operate at 4K - reduce cryogenics system cost
- Strong Medium Field Q-Slop (MFQS) is observed at 4K in low frequency and low β resonators.
- Presently facilities are choosing to operate at 2K even at low frequency to avoid MFQS (ie FRIB and RISP).
- MFQS and improving 4K performance need to be further understood.
- Example: 120˚C bake improves 4K Q in medium field.

FRIB 80.5MHz β=0.085 QWR

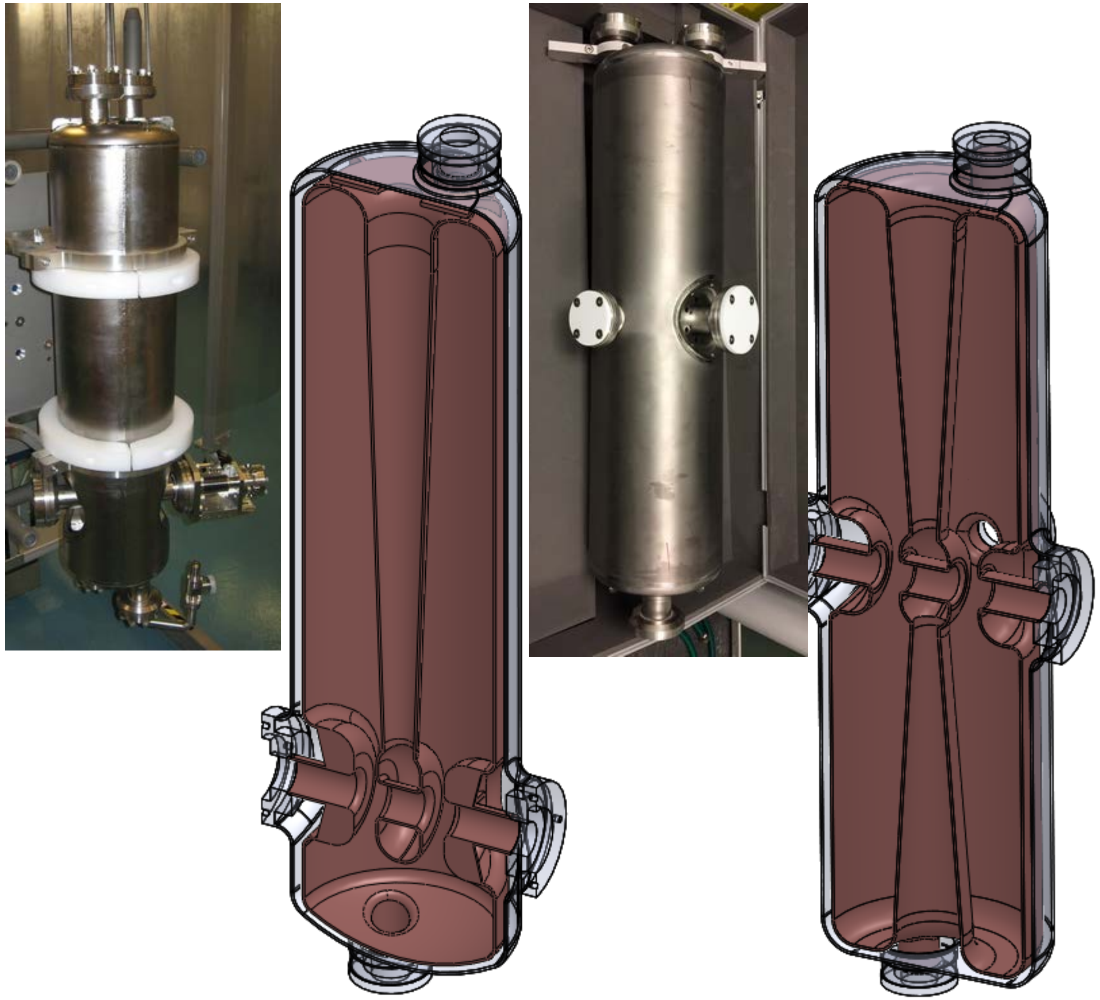


K. Saito, 'FRIB Project: Moving to Production Phase', SRF2015

Study: RISP QWR and HWR Cavities

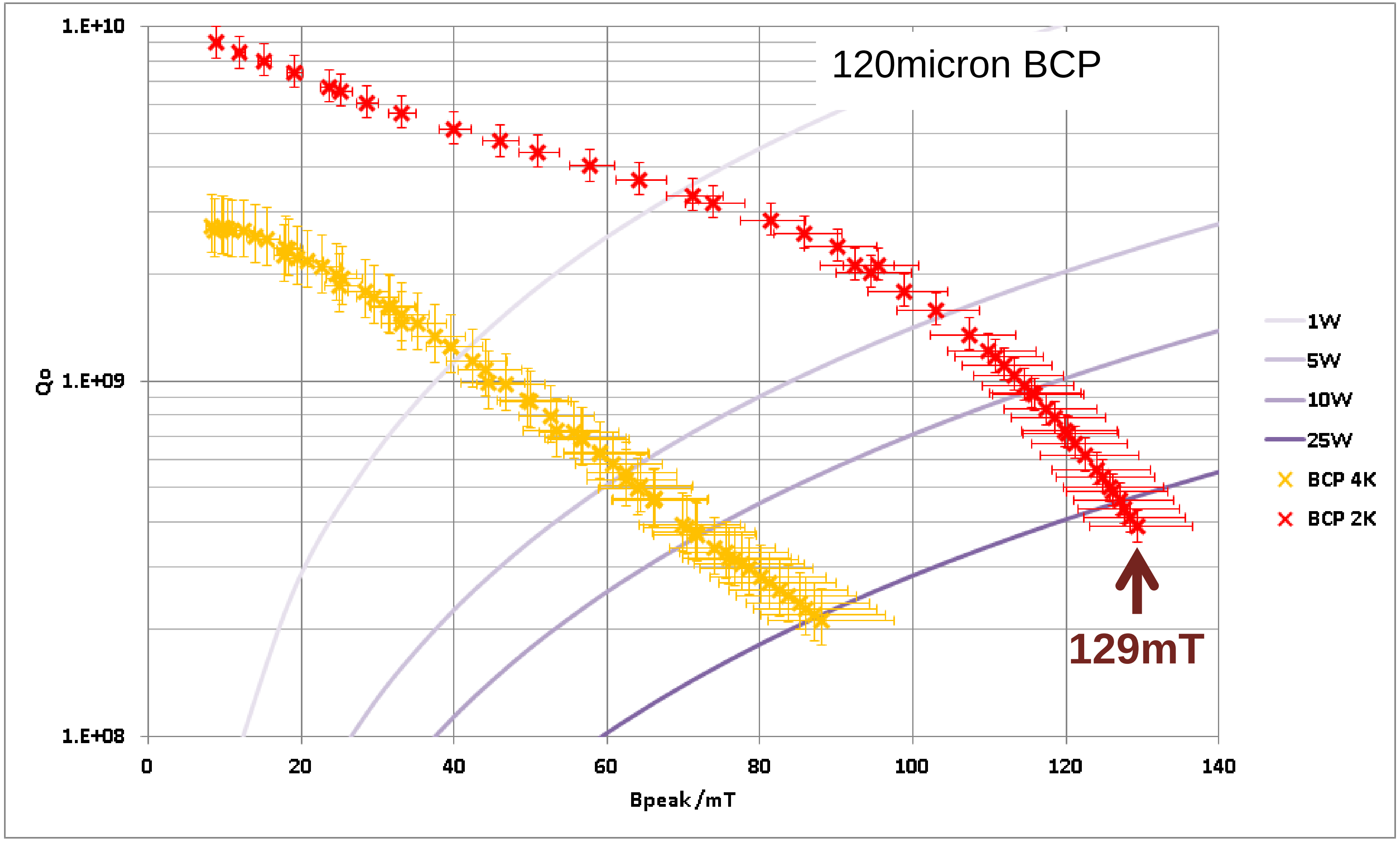
- 81.25MHz QWR and 162.5MHz HWR designed by RISP
- Cavity treatments
  - 120µm BCP (+15µm for HWR)
  - HPR
  - 48hr 120°C bake
- Cavities were tested at TRIUMF before and after bake and after multiple etches

	QWR	HWR	Unit
Frequency	81.25	162.5	MHz
β	0.047	0.12	1
$L_{eff}=\beta\lambda$	0.173	0.221	m
E_{peak}/E_{acc}	5.3	5.6	1
B_{peak}/E_{acc}	9.5	8.2	mT/MV/m
G	21	40	Ω
U/E_{acc}^2	0.126	0.159	$J/(MV/m)^2$



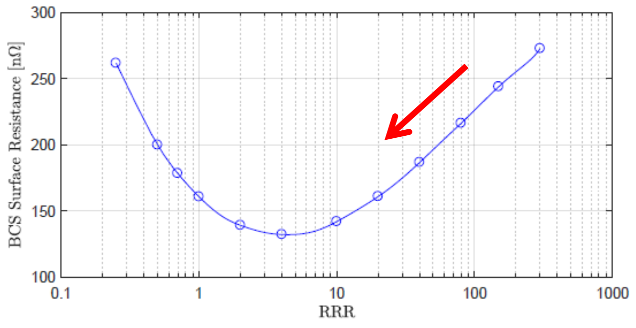
QWR BCP Result

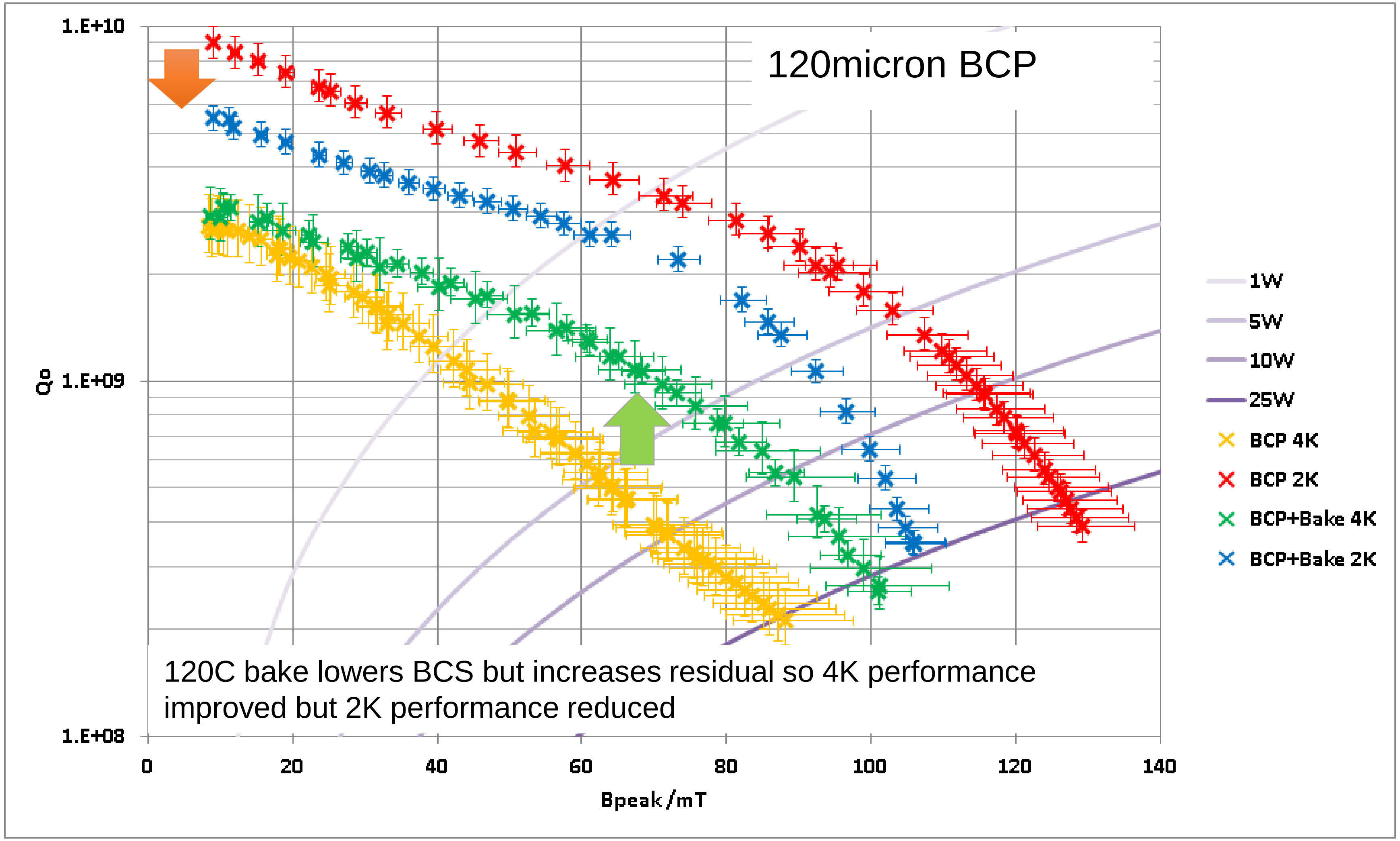
- QWR was etched 120microns
- Tested at 4.2K and 2K
- Significant Q-slope at 4K – less slope at 2K



QWR 120C Bake

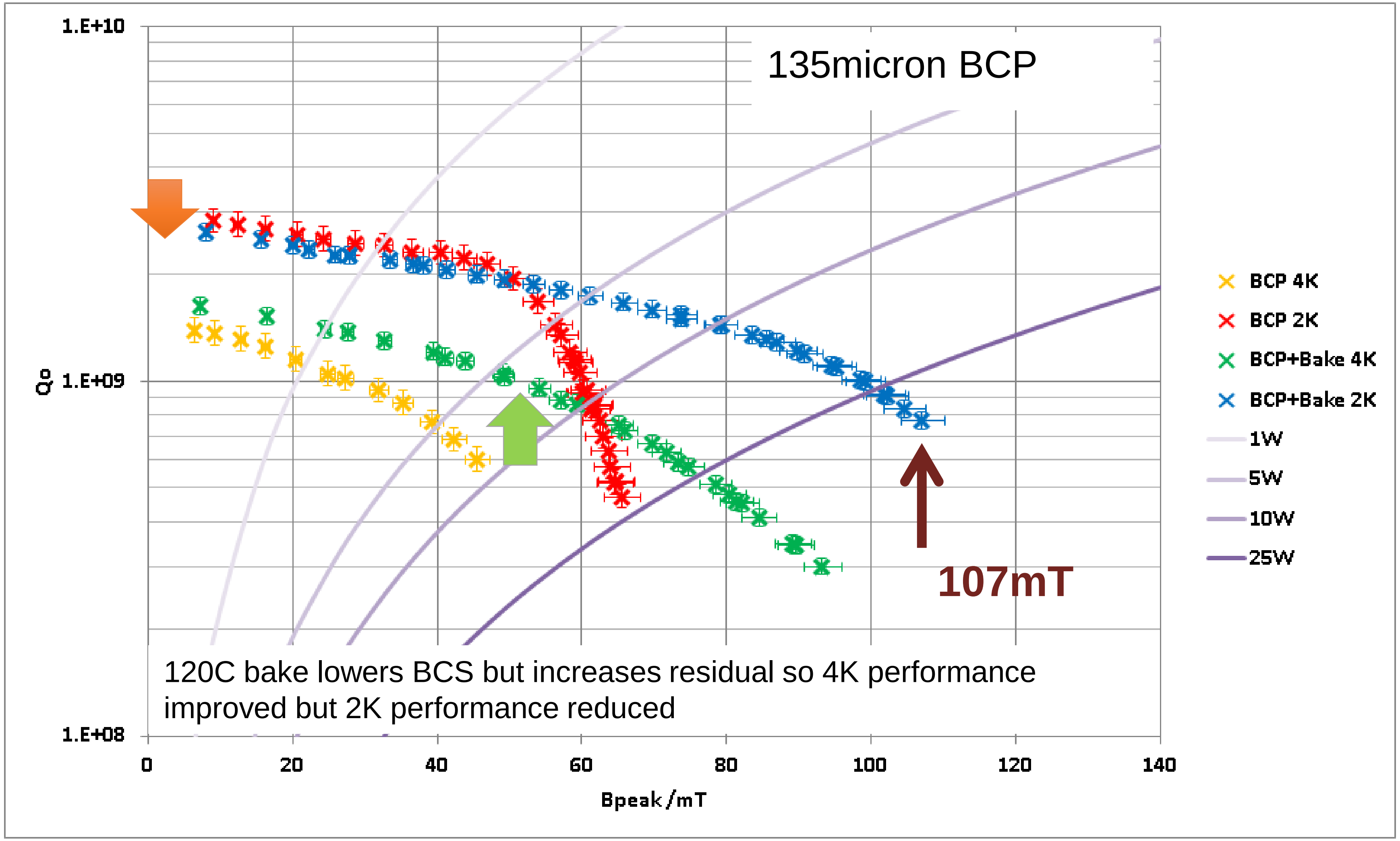
- 120C Bake applied for 48 hours
- The bake modifies the MFP within the surface layer and improves R_{BCS} at the expense of increasing the residual R_{res}





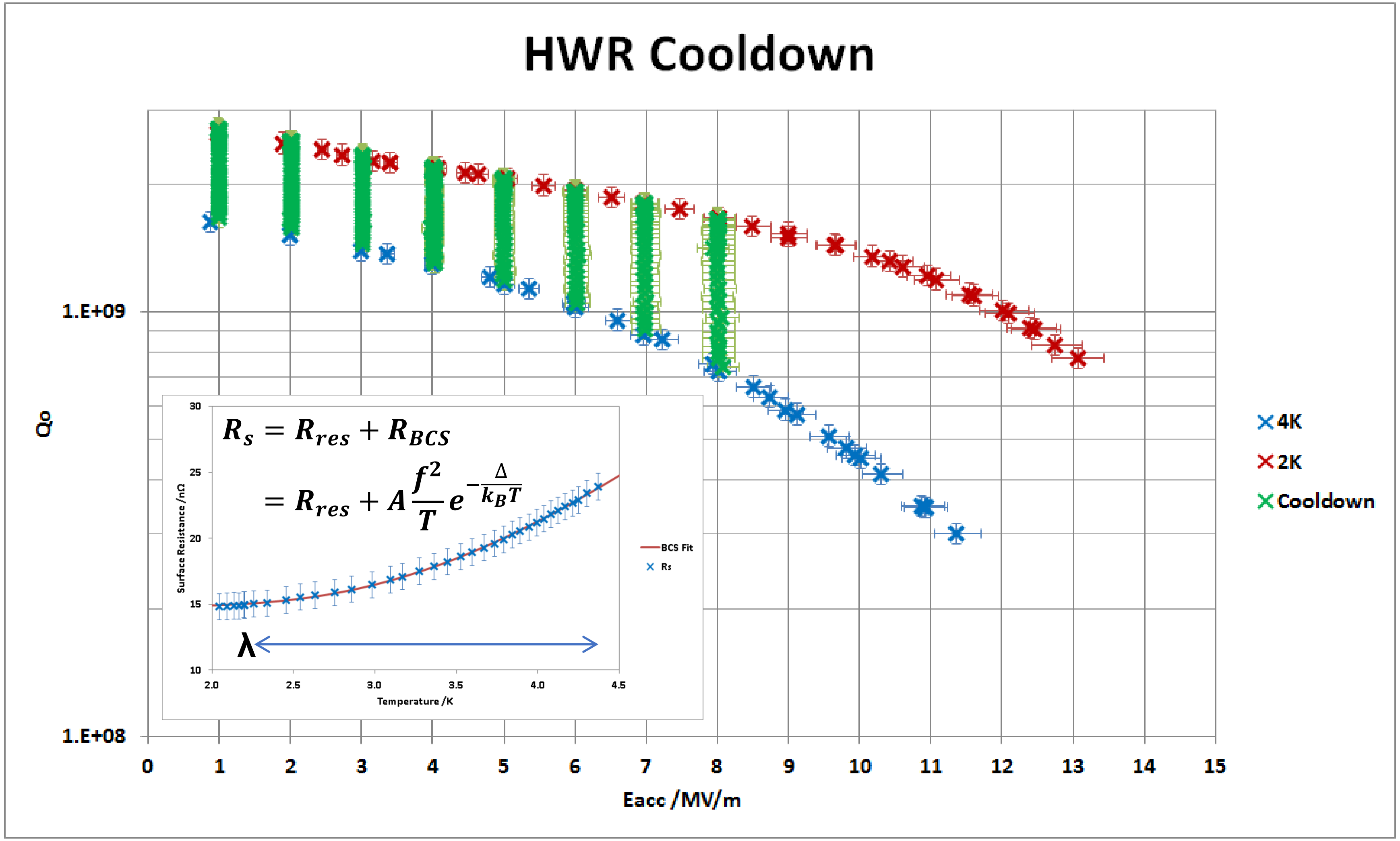
HWR Before and After 120C Bake

- The same measurement sequence was done with the HWR cavity
- BCP 2K result impacted by FE near 55mT



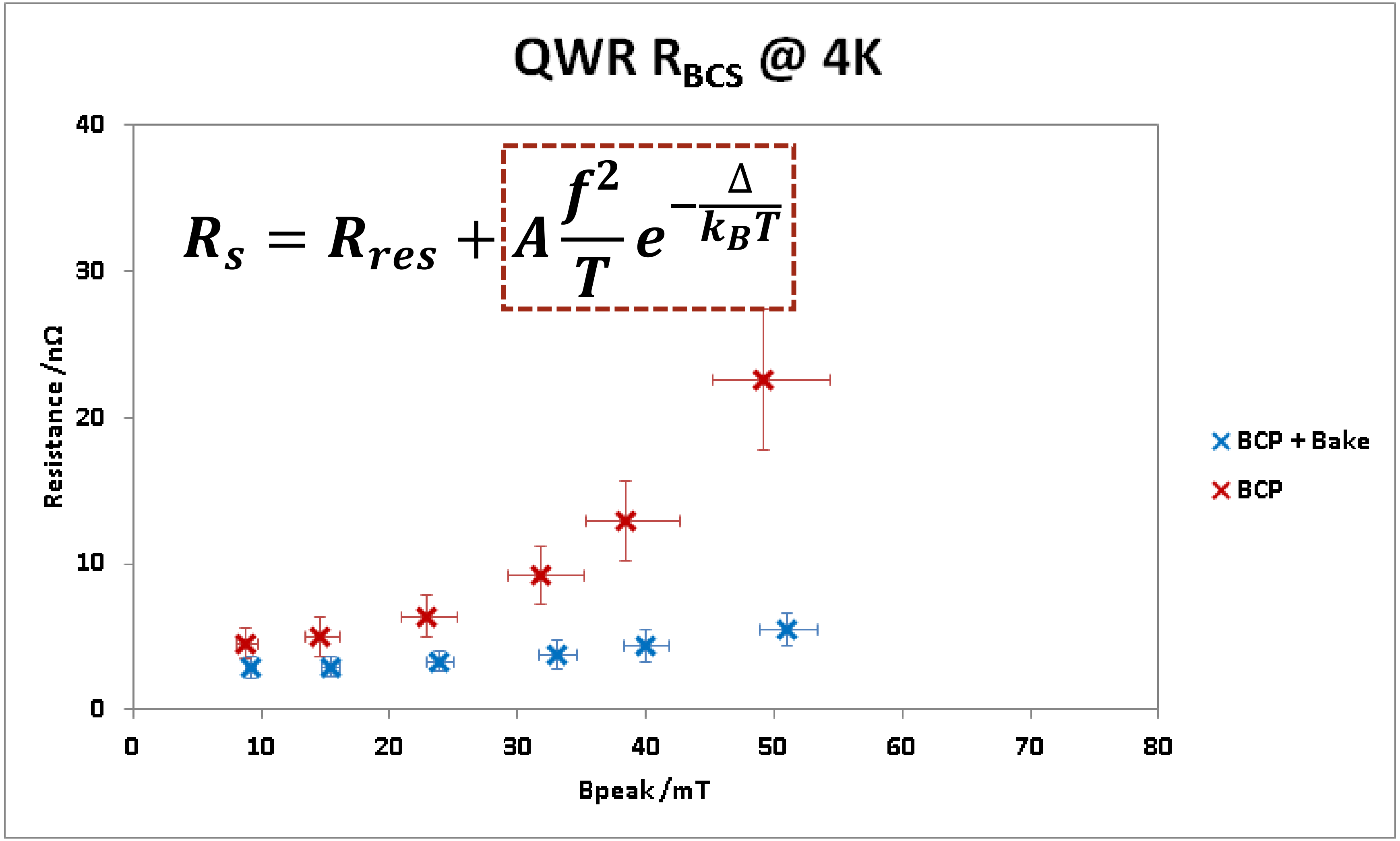
4K to 2K Data to Extract R_{BCS} and R_{res}

- To separate R_{BCS} and R_{res} components, Q measurements are taken at various field levels and temperatures as the cavity is cooled down
- R_{BCS} is expected to follow a exponential dependence with temperature



QWR BCS Resistance

- Manipulation of the data can be done to extract R_{BCS} as a function of field
- Note how the 120C bake has lowered the base R_{BCS} and significantly decreased the field dependence

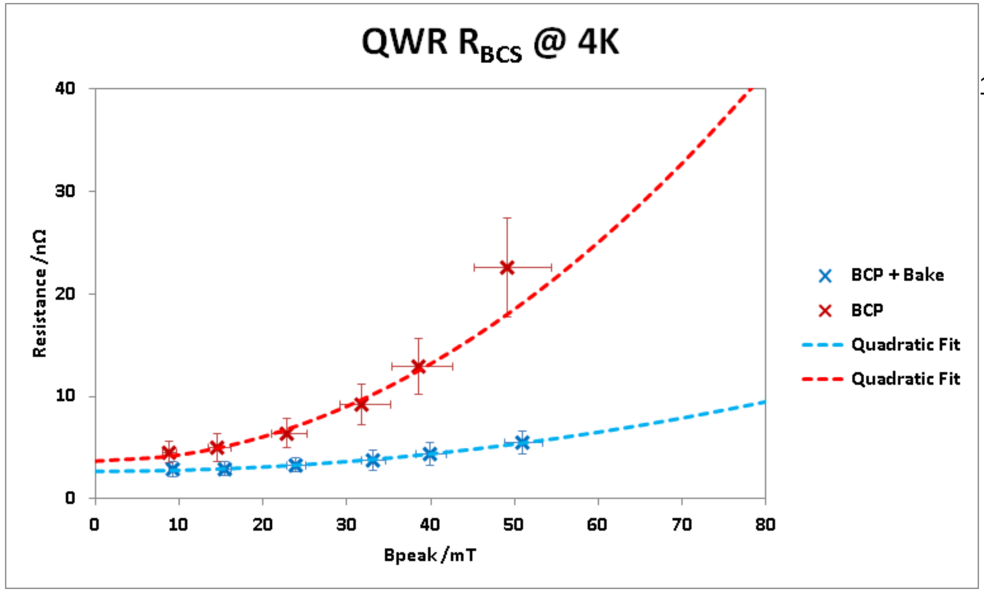


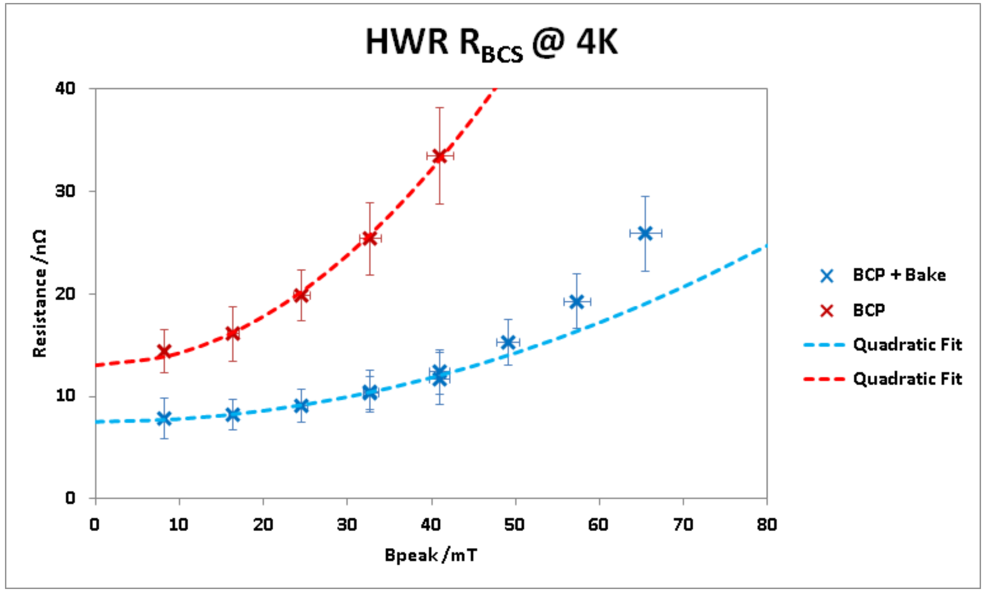
Quadratic Dependent R_{BCS}

- 120C Bake reduced R_{BCS0} and field dependent coefficient.
- Field dependence is quadratic for B_{peak}<40mT.
- Slope is stronger than quadratic at the field of >60mT.

$$R_{BCS} = R_{BCS0}\left(1 + \gamma\left(\frac{B_p}{B_C}\right)^2\right)$$

	R_{BCS0} @ 4K nΩ	γ
QWR BCP	**3.70**	**64.2**
QWR Bake	**2.69**	**15.8**
HWR BCP	**13.03**	**36.7**
HWR Bake	**7.53**	**14.3**



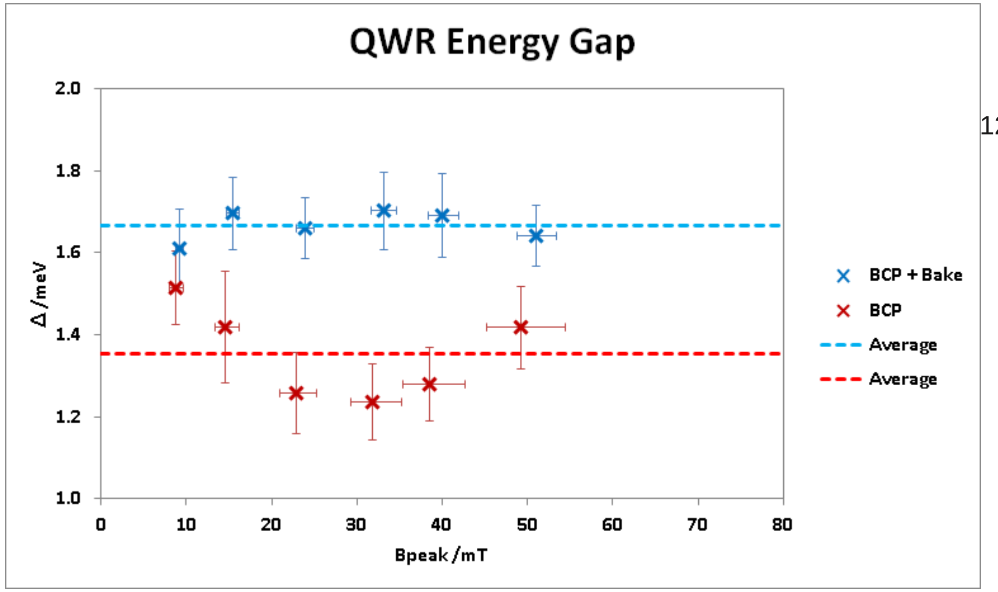


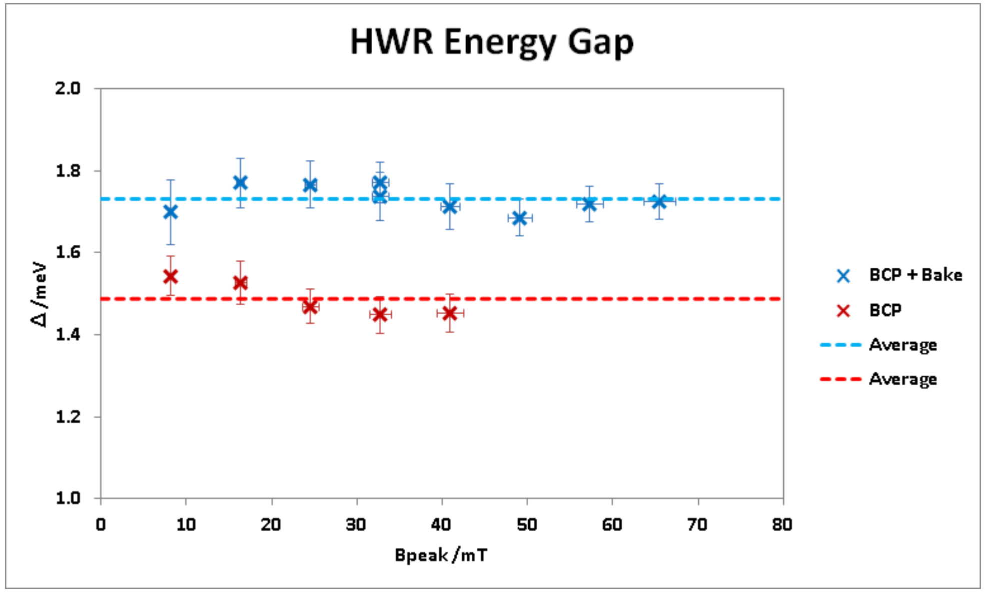
Energy Gap

- Field dependence of energy gap is not obvious in low and medium field.
- Bake increased average value of energy gap by about 20%.

$$R_{BCS0} = A^* \frac{f^2}{T} e^{-\frac{\Delta}{k_B T}}$$

Δ meV	QWR	HWR
BCP	1.35	1.49
Bake	1.67	1.73



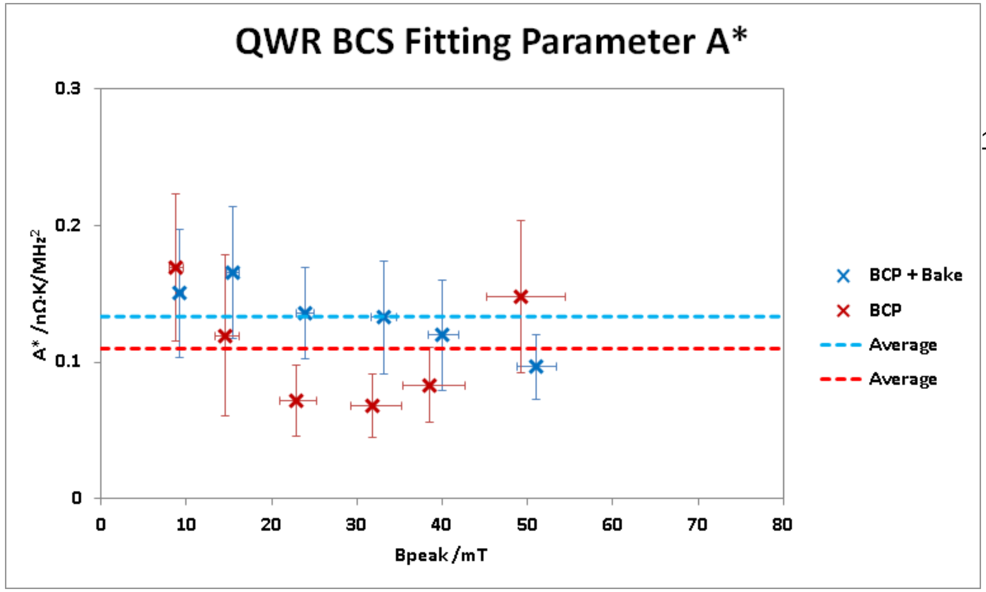


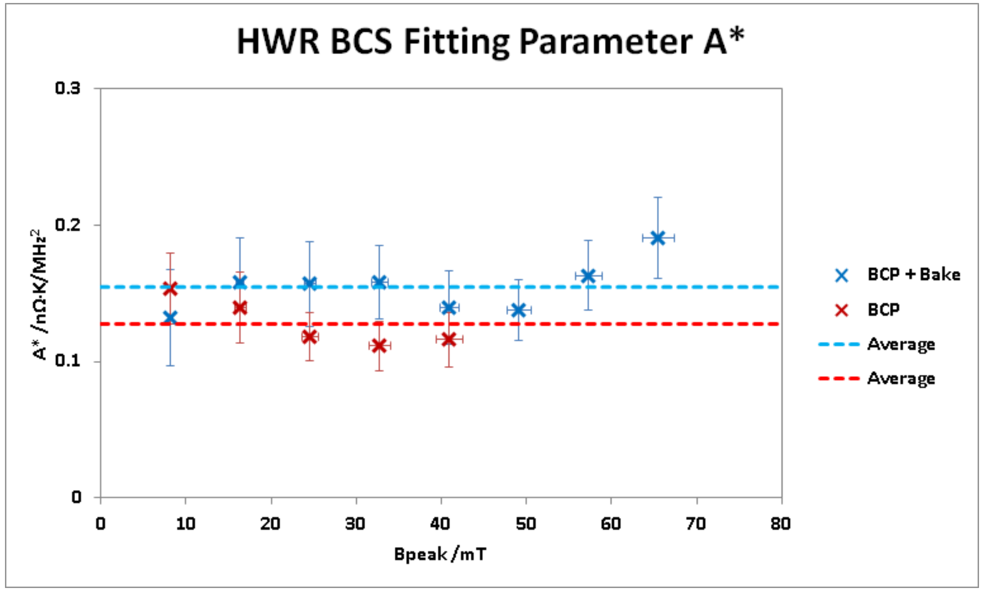
Fitting Parameter A*

- Bake effect for A* is not obvious with these two data set. The differences are within error bars.

$$R_{BCS0} = A^* \frac{f^2}{T} e^{-\frac{\Delta}{k_B T}}$$

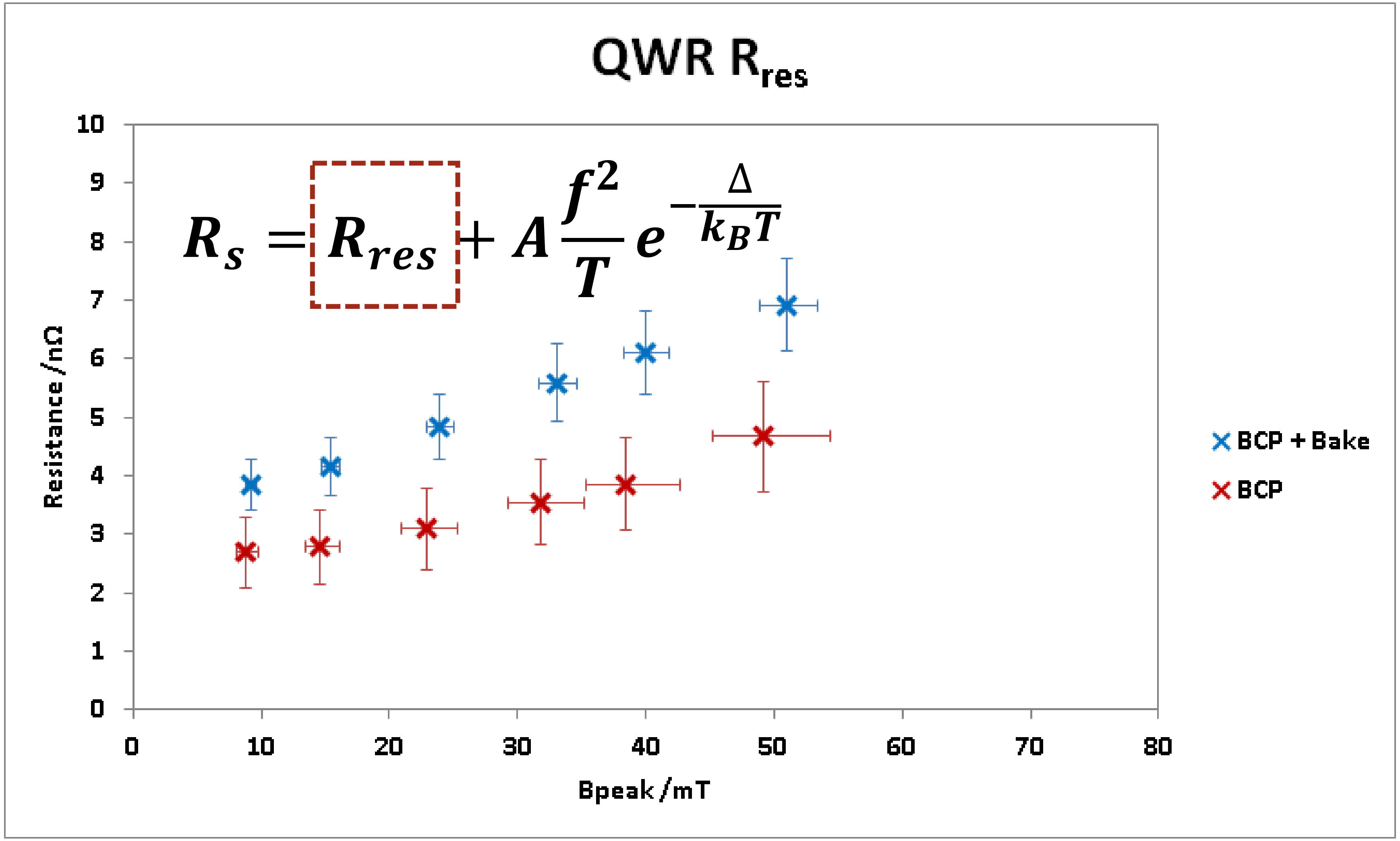
A* nΩ·K/MHz²	QWR	HWR
BCP	0.110	0.128
Bake	0.133	0.155





QWR Residual Resistance

- R_{res} corresponds to the non exponential term
- Also responsible for Q-slope but this looks more linear

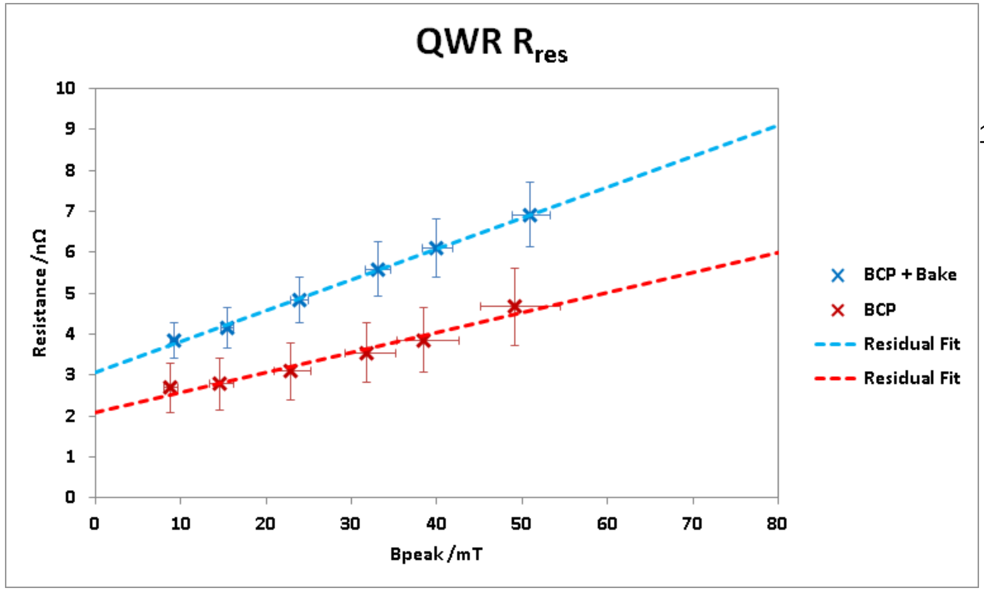


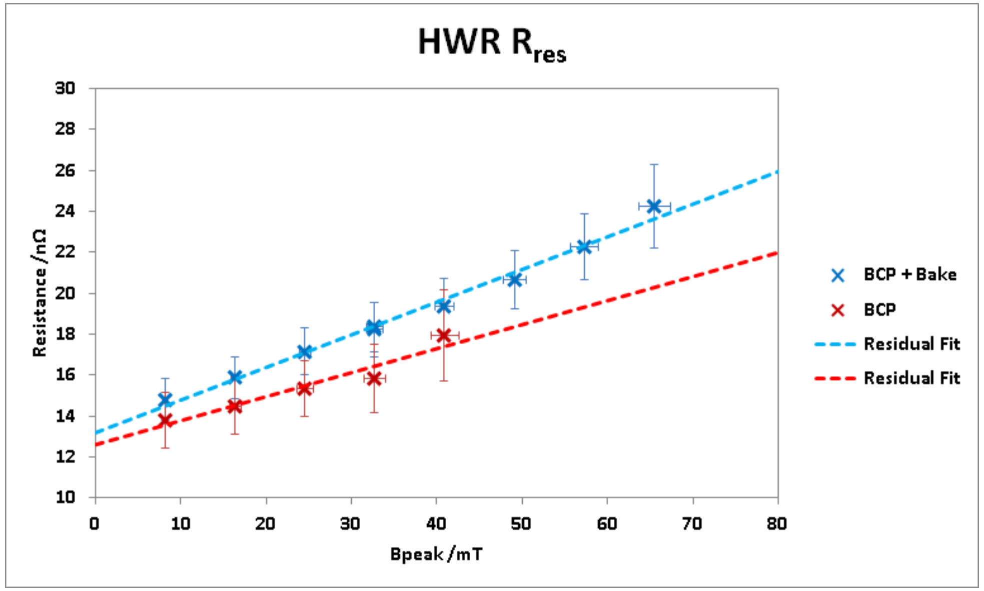
Linear Dependence of R_{res}

- Bake increased R_{res0} and field dependent slope.
- High R_{res} of HWR is suspected due to cool down procedure and trapped flux.
- R_{res1} is proportional to frequency within error bar.

$$R_{res} = R_{res0} + R_{res1}\left(\frac{B_p}{B_C}\right)$$

	R_{res0} nΩ	R_{res1} nΩ
QWR BCP	2.09	9.76
QWR Bake	3.07	15.1
HWR BCP	12.6	23.5
HWR Bake	13.2	31.9





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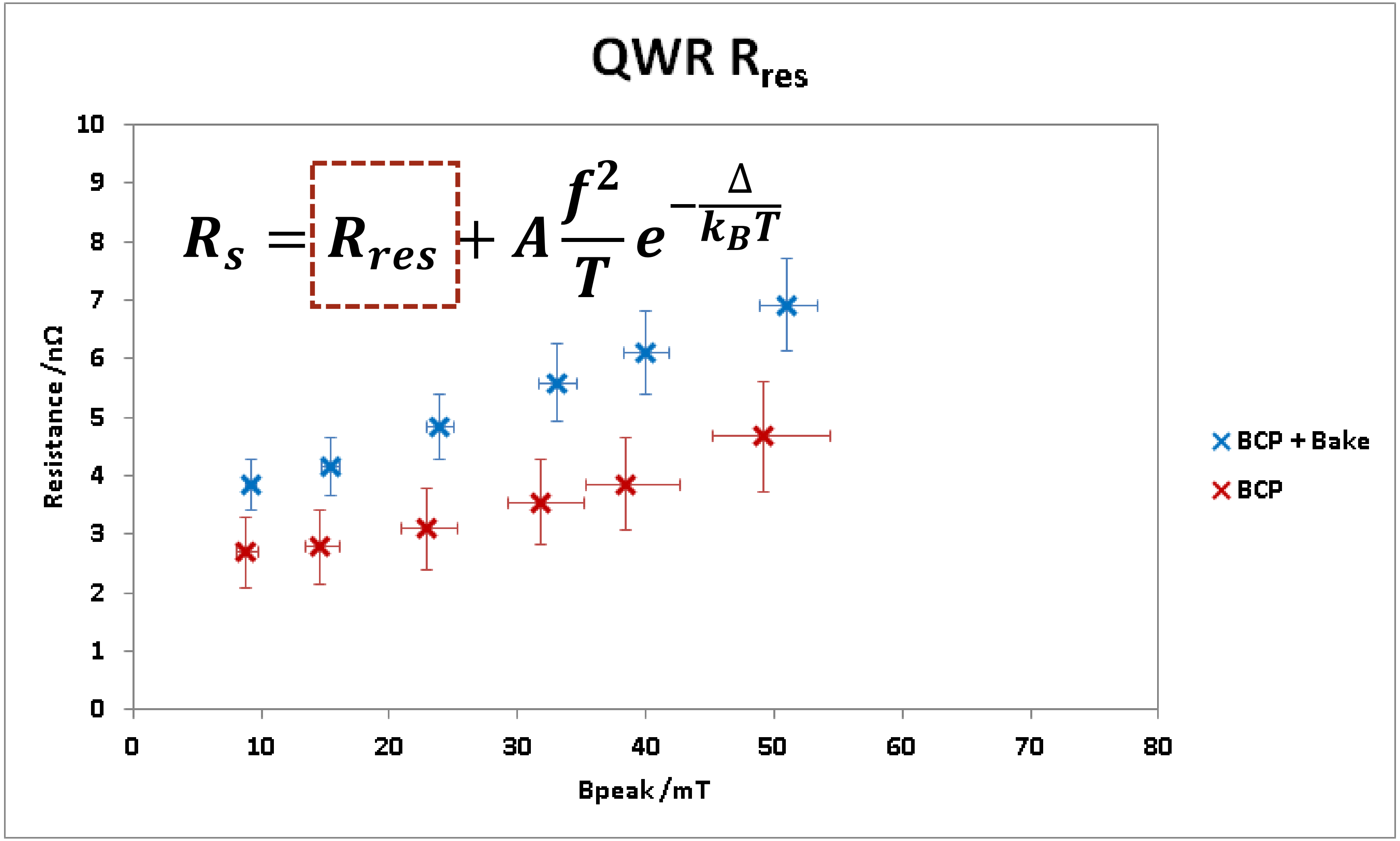
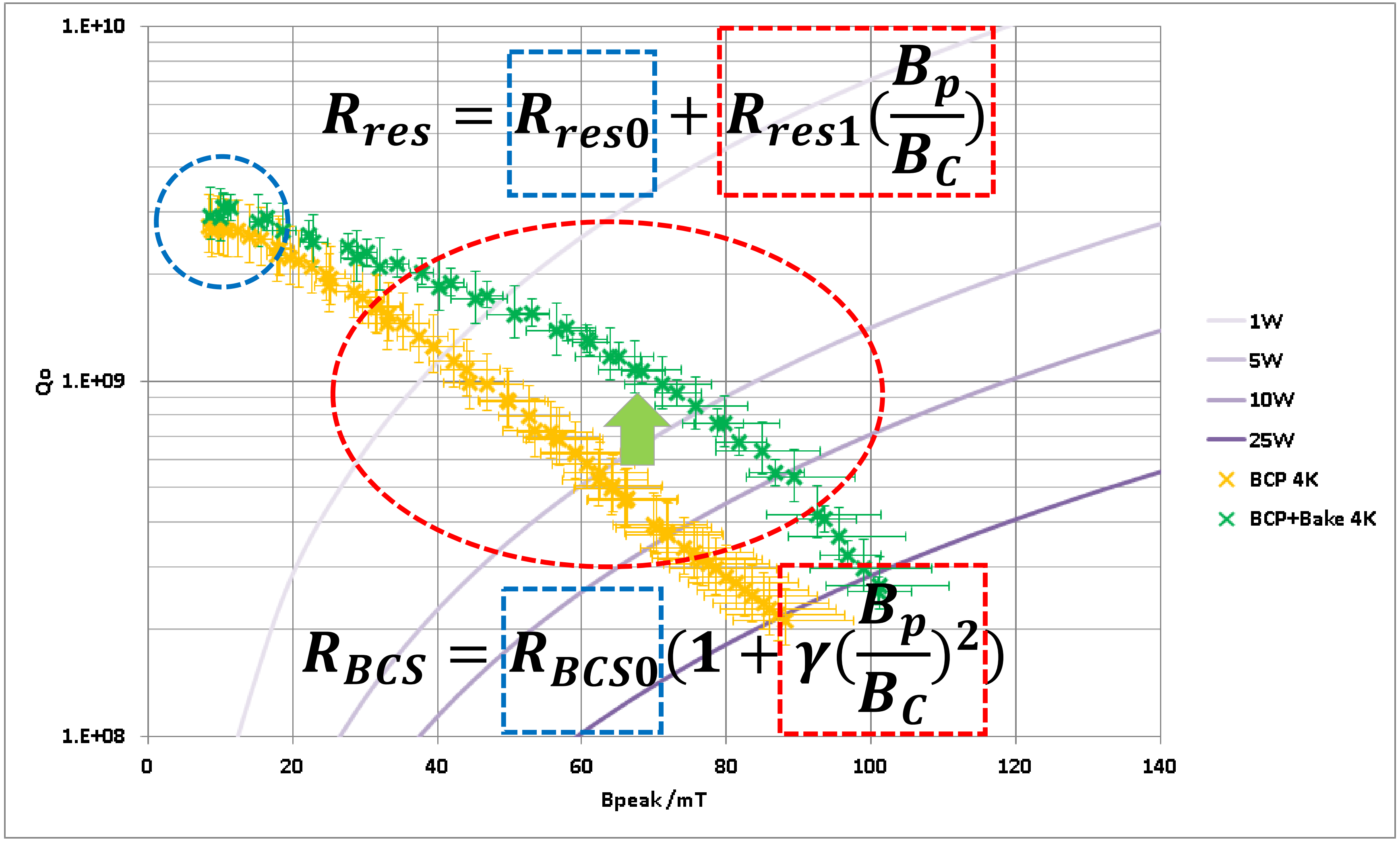


QWR 4K Q-slope

- The Q-slope is a combination of R_{BCS}(B) and R_{res} (B)
- Both linear and quadratic terms are identified



Geometry Factor

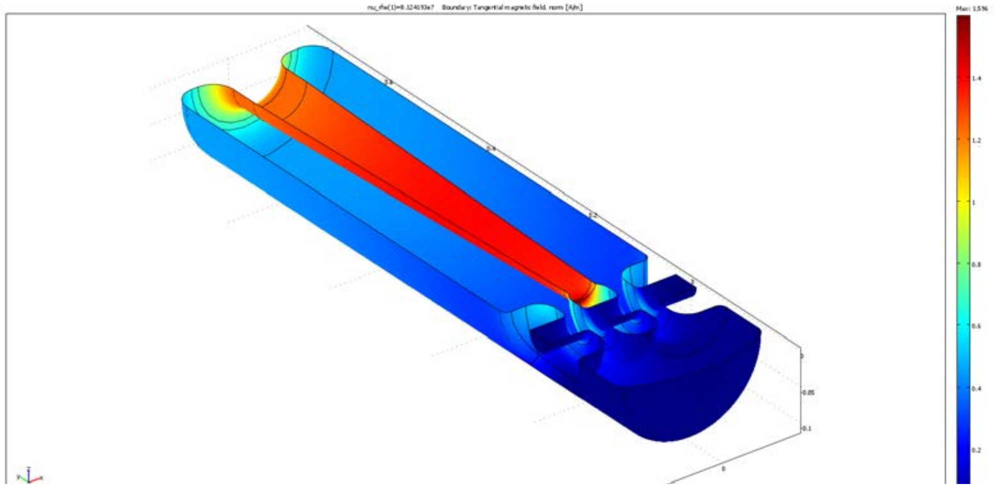
- Comparing performances of field dependent Rs across different cavities requires more than $Q_0(B)=G/R_s(B)$ since G is dependent on $R_s(B)$
- Extracting accurately the surface resistance from experimental data requires to take into account the field distribution over the accelerating structure

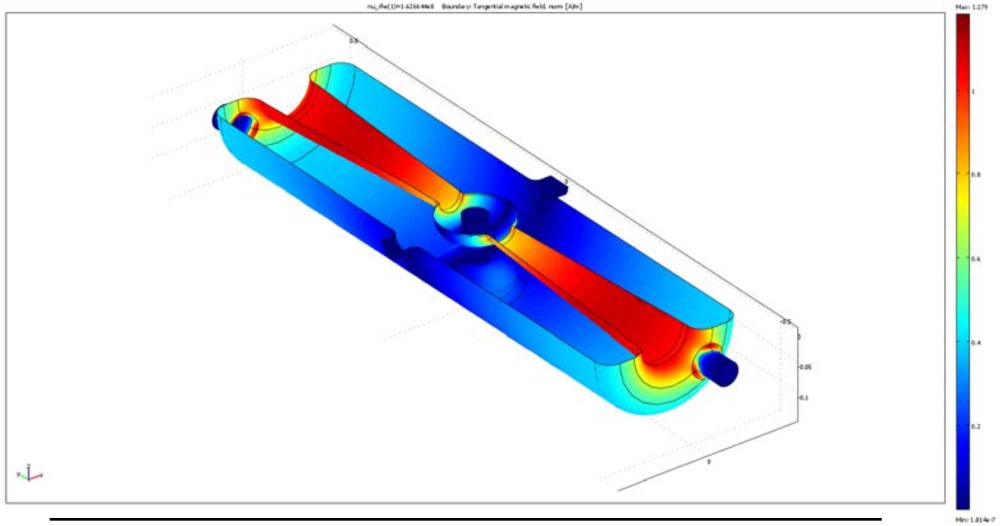
$$\frac{G}{Q_0} = R_s \quad \Rightarrow \quad \frac{G}{Q_0} = \frac{\int R_s(B)|B|^2 ds}{\int |B|^2 ds}$$

$$R_s(B) = R_{s0} + \alpha_1 |B| + \alpha_2 |B|^2$$

$$\frac{G}{Q_0} = R_{s0} + \alpha_1 \beta_1 B_p + \alpha_2 \beta_2 {B_p}^2$$

$$\beta_n = \frac{\int (|B|/B_p)^{n+2} ds}{\int (|B|/B_p)^2 ds}$$





	QWR	HWR
β_1	0.68	0.71
β_2	0.53	0.58

From $R_s(B_p)$ to $R_s(B)$

$$R_{res} = R_{res0} + R_{res1}\left(\frac{B_p}{B_C}\right)$$

$$R_{BCS} = R_{BCS0}\left(1 + \gamma\left(\frac{B_p}{B_C}\right)^2\right)$$

$$R_{res} = R_{res0} + R_{res1}{}^{*}\left(\frac{B}{B_C}\right)$$

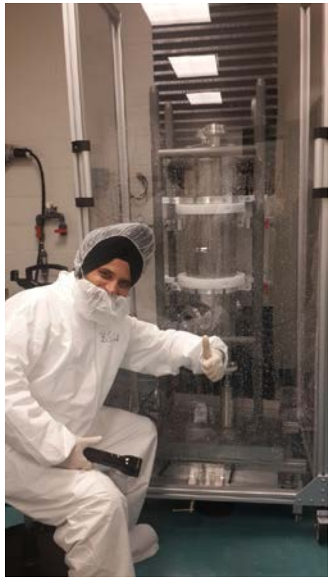
$$R_{BCS} = R_{BCS0}\left(1 + \gamma^{*}\left(\frac{B}{B_C}\right)^2\right)$$

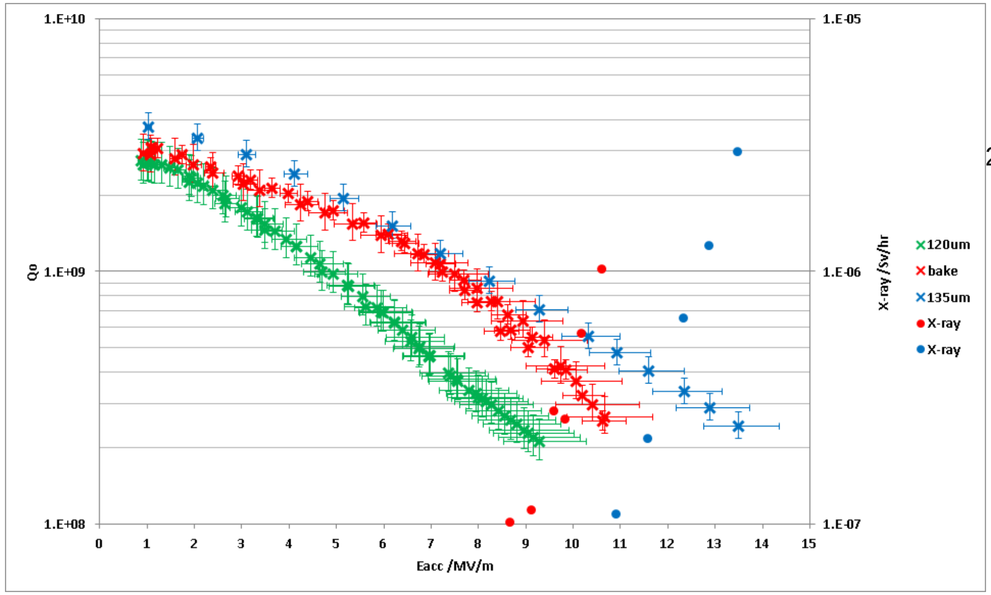
- After corrections the true linear and quadratic $R_s(B)$ field dependence can be determined

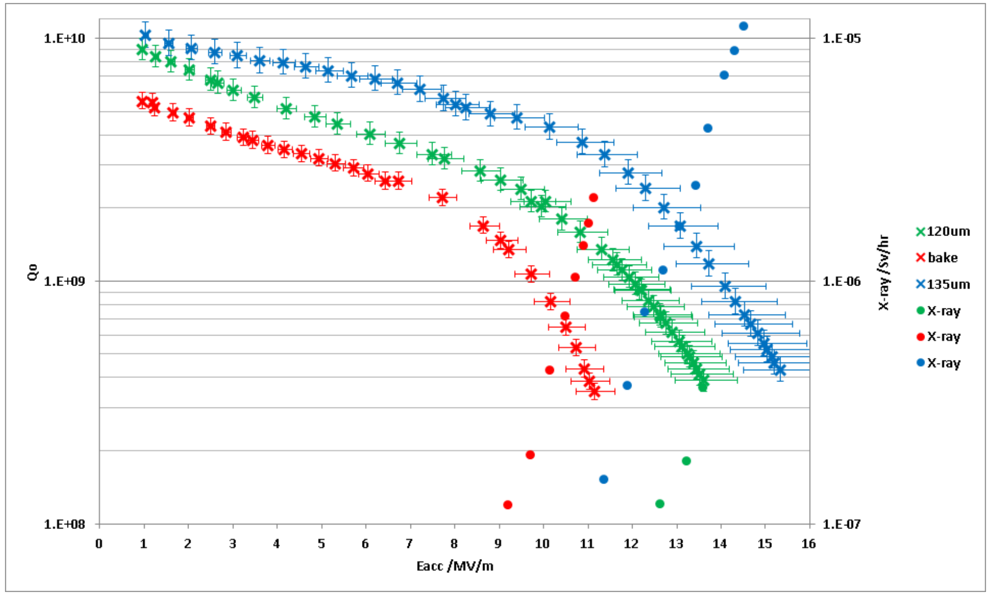
	R_{res1} nΩ	$R_{res1}{}^{*}$ nΩ	γ	γ*
QWR BCP	9.76	14.4	64.2	121.6
QWR Bake	15.1	22.2	15.8	29.9
HWR BCP	23.5	32.9	36.7	63.6
HWR Bake	31.9	44.7	14.3	24.8

QWR - 135μm BCP

- After the first round of tests the cavity was given a further 15microns etch and the performance improved.
- The etch destroys the previous R_{BCS} improvement from the 120C bake but reduces the residual and the residual slope

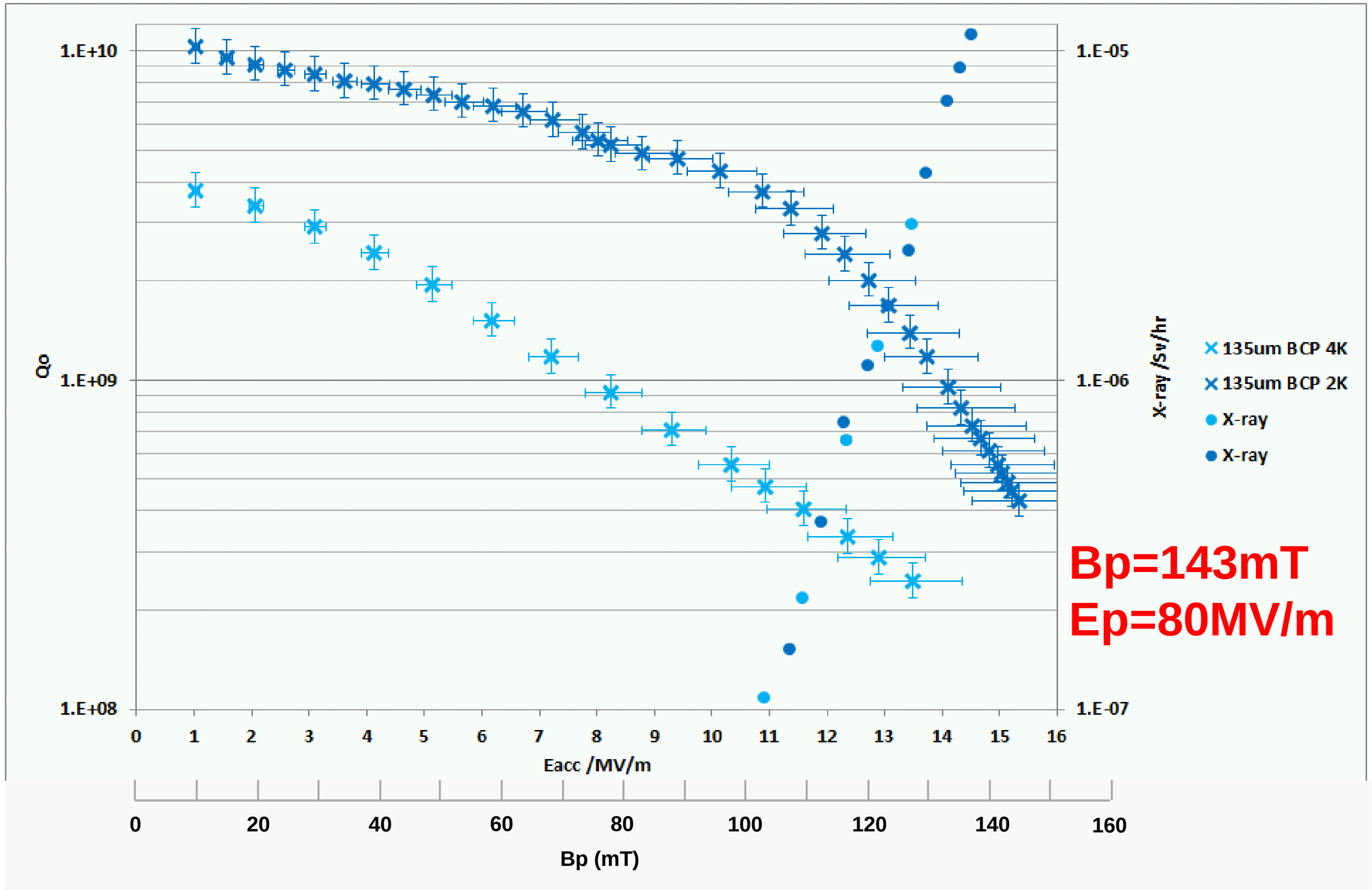






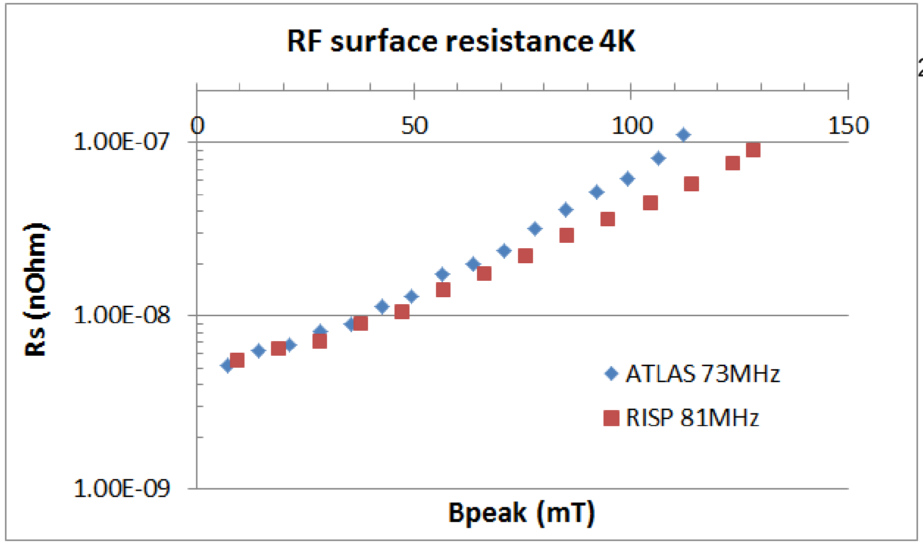
QWR – High performance

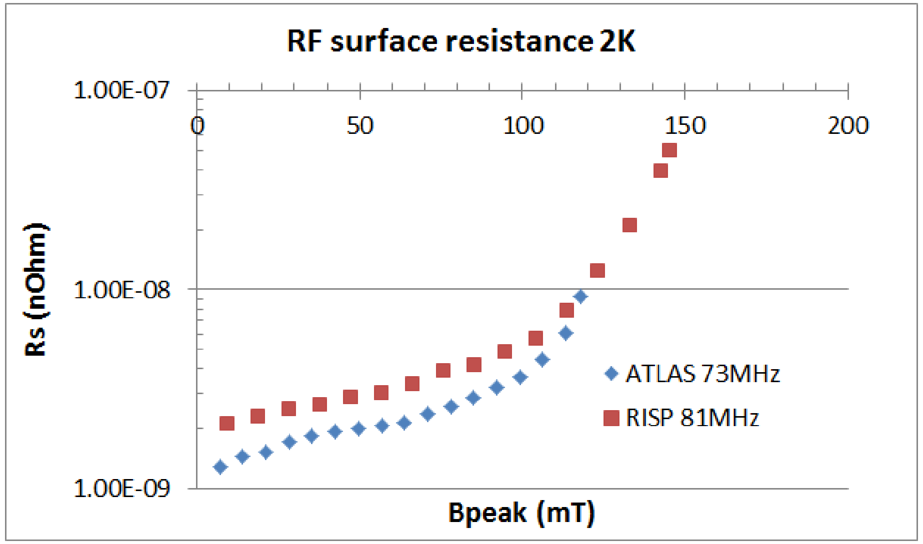
- Note that the cavity pushes out to high field with some FE but no quench to Bp=143mT or Ep=80MV/m
- Corresponds to Ea~33MV/m for an elliptical cavity
- Excellent performance for a BCP cavity



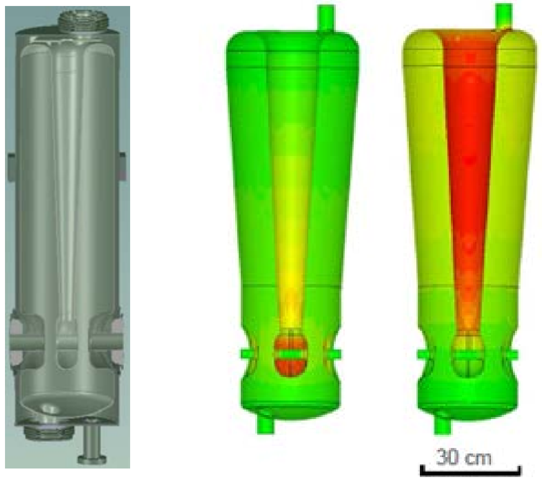
ANL (EP) vs RISP QWR (BCP)

- Elliptical cavities typically choose EP for high gradient performance – Low beta typically chooses BCP
- Here's a comparison of Rs for ANL QWR (EP) and RISP QWR (BCP) both at 4K and 2K. ANL cavity has a slightly better residual resistance at 2K but Q-slope is actually slightly better in RISP case with higher final Bp.
- Bottom line is that both BCP and EP can deliver great performance. The heat treatment after processing can play a significant role.





Cavity type	QWR
Freq. (MHz)	81.25
β	0.047
Leff (cm, βλ)	17.3
Ep/Ea	5.3
Bp/Ea	9.5
QRs (Ohm)	21
Rs/Q (ohm)	470



Cavity Type	QWR
Freq. (MHz)	72.75
β	0.077
l_{eff} (cm, βλ)	31.75
E_{pk}/E_{acc}	5.0
B_{pk}/E_{acc} (mT/(MV/m))	7.1
QR_s (Ω)	25.9
R_{sh}/Q (Ω)	568

Summary

- MFQS study was performed on two low β resonators by measuring cool down Q data at various field levels.
- 120˚C bake improved 4K performance in medium field for both RISP QWR and HWR by reducing R_{BCS0} and field dependent coefficient. The 120C bake increased R_{res}.
- With our data, the field dependent component of BCS resistance is shown to be quadratic, and the residual part is linearly field dependent.
- More systematic tests and data from the community can give an insight of MFQS for low β resonators.
- To compare the field dependent surface resistance of different structures the distribution of the field on the surface has to be taken into account.

Thank You

Merci

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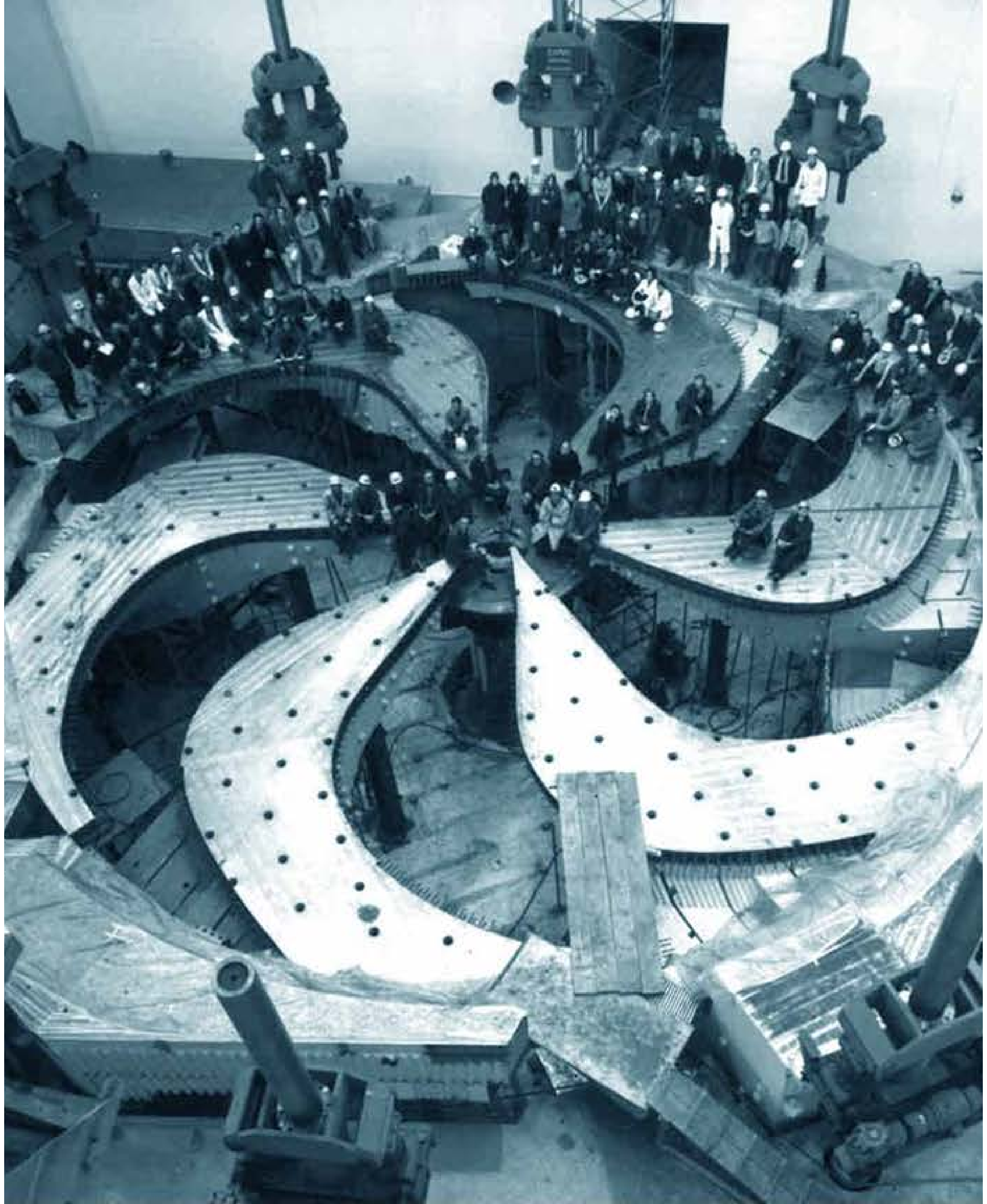

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