Q-slope analysis of global data and new techniques for Q-slope studies

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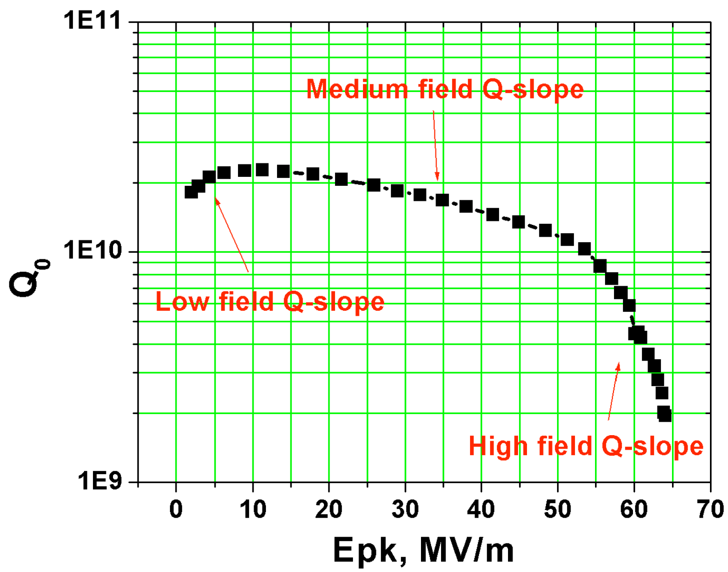
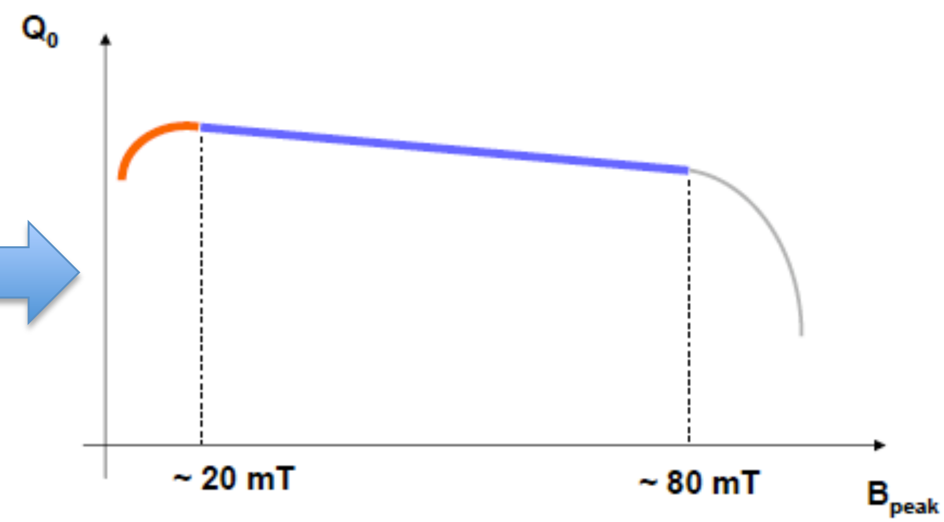
Outline

- Q-slopes: the high beta definition
- A well defined problem?
- The low beta world
- Trends for low beta and comparison with high beta
- New technique for Q-slopes studies: muSR @ TRIUMF

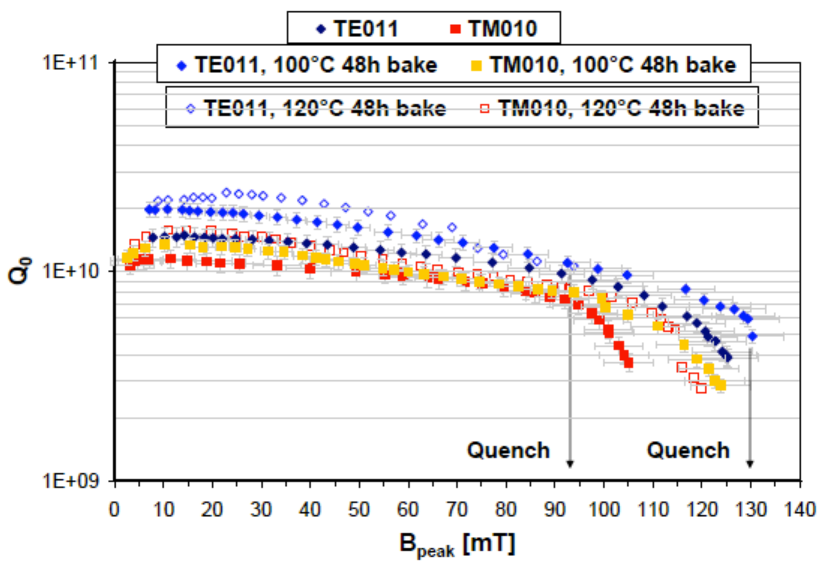
Q-slope: the high beta definition

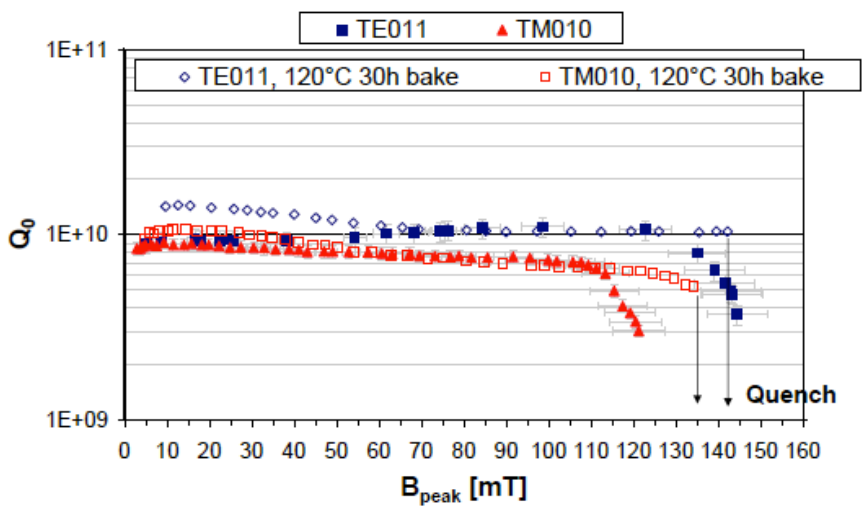




A well defined problem? High beta

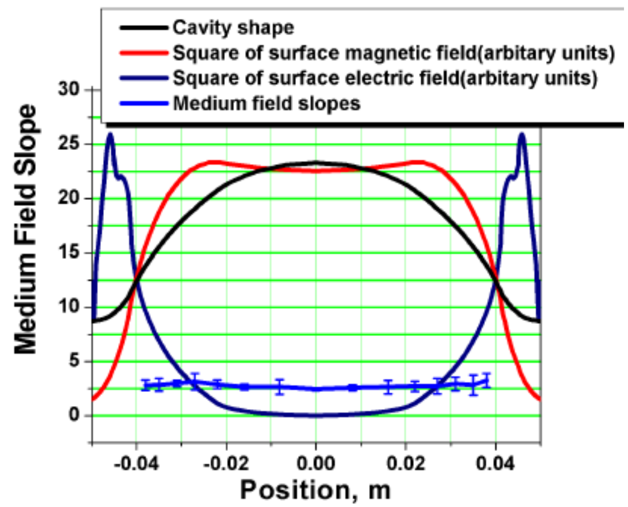
- We define three different problems based on slope trends. Is this the correct approach?
- Global or localized effect? Magnetic field effect? Electric?
- Some test (Ciovati-Jlab, Eremeev-Cornell) show peak magnetic fields responsible for HFQS, what about Medium Field Q-slope?

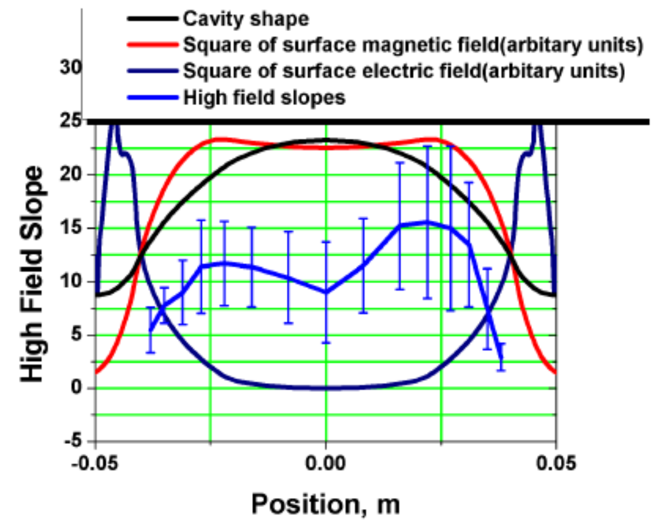




A well defined problem? High beta

Analysis of correlation between the slope in the medium and high field regions performed on the BCP not baked cavity – Cornell data (G. Eremeev, PhD thesis) – **homogeneity** of MFQS is concluded

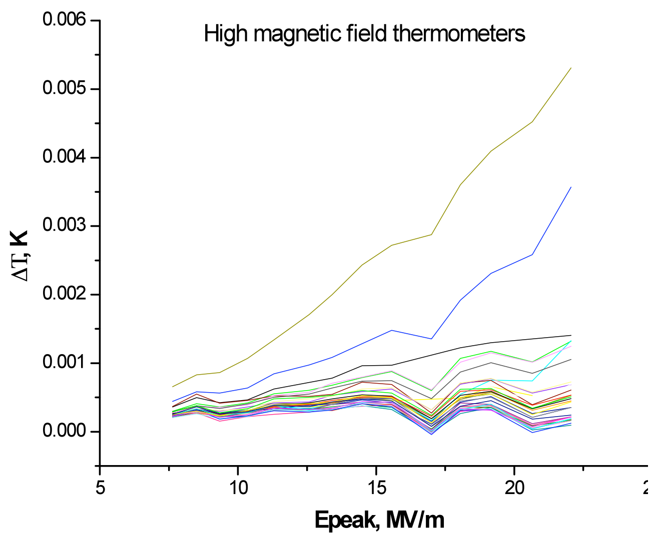


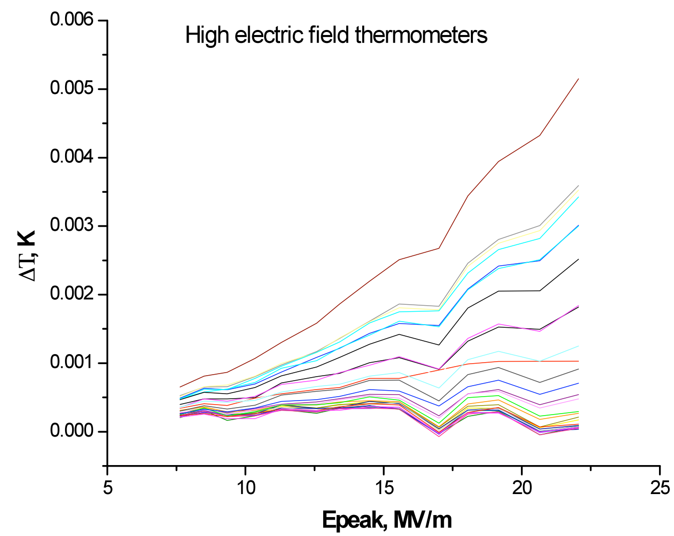


•Spread in individual dT(H) curves observed in Fermilab EP baked cavity in the medium field region – spatial **non-homogeneity** is observed, especially in the high electric field region

•Need for more thermometry/cutout studies

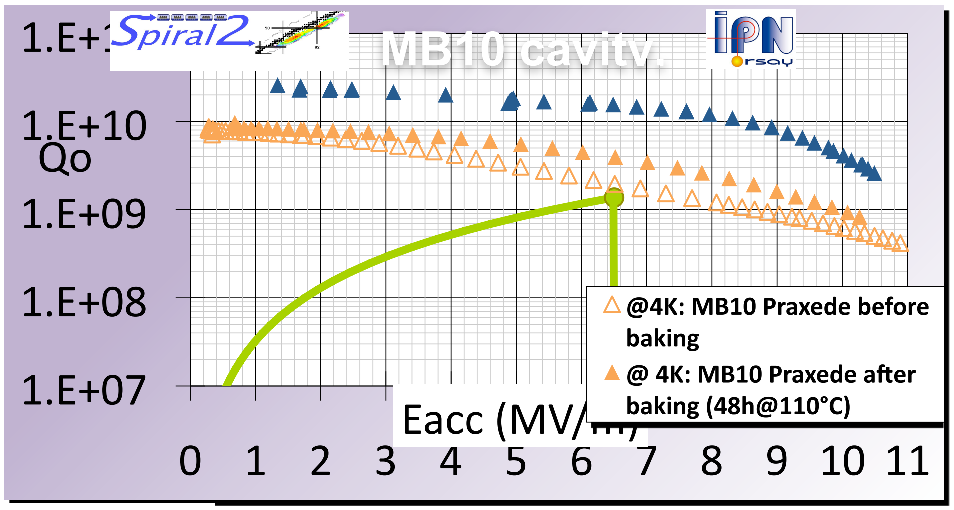
•At TRIUMF with muSR





Q-slope in the low beta world

- Do definitions of high beta/low beta Q-slope coincide?
- What is Q-slope at low, medium and high field regimes in low beta cavities?



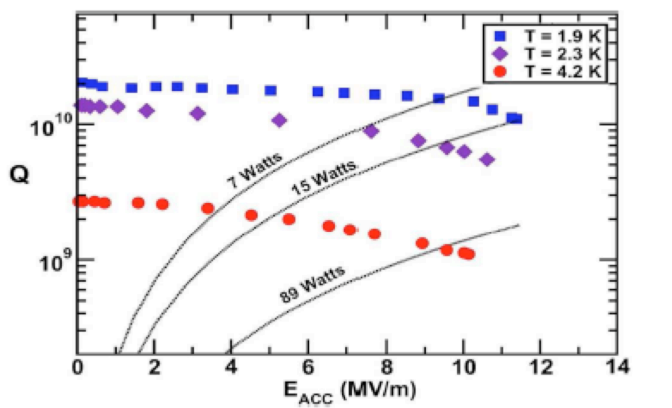


Figure 8: Q-curve test results (colored symbols) and lines of constant rf power for a 345 MHz β=0.63 triple-spoke cavity developed at ANL. At T=2 K, 7 Watts input power gives and energy gain of 7 MV/cavity.

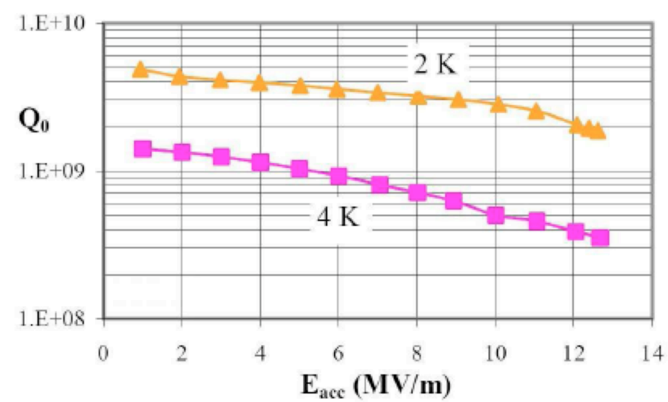


Figure 7: Q-curve test results for a 350 MHz β=0.175 single-spoke cavity developed at LANL.

Q-slope analysis: approaches

- Model surface resistance and use the model to find fitting values for different parameters: better a posteriori (based on experimental evidence)
- Fit and look for trends in: temperature, treatments, frequency: it might allow to find correlation and draw conclusions

Trend analysis

- LF-MF-HFQS, peak magnetic field range <20mT, 20-60mT, above 60mT
- Low beta cavities analyzed include ~50 cavities: QWR TRIUMF ISAC2 phase 1 (106MHz) and 2(141MHz), SPIRAL2(88MHz), MSU(80.5MHz), SPOKE ANL(345MHz), LANL(350MHz), ORSAY (352MHz)
- High RRR, 2-3mm walls, standard treatments include BCP (80-200microns), HPR, EP for ANL
- MFQS: Quadratic and linear fit:

$$R_s = R_0\left(1 + \gamma\left(\frac{H}{H_c}\right)^2\right) + R_1\left(\frac{H}{H_c}\right)$$

On G/Rs

Definition of quality factor: $$Q_0 = \frac{\omega U}{P_{diss}} = \frac{\omega \int\limits_{volume} \frac{1}{2}\mu_0 H^2 dv}{\int\limits_{surface} \frac{1}{2} R_s(H) H^2 ds}$$

But magnetic field is NOT constant over cavity surface and IF AND ONLY IF Rs(H) = const it can be simplified to

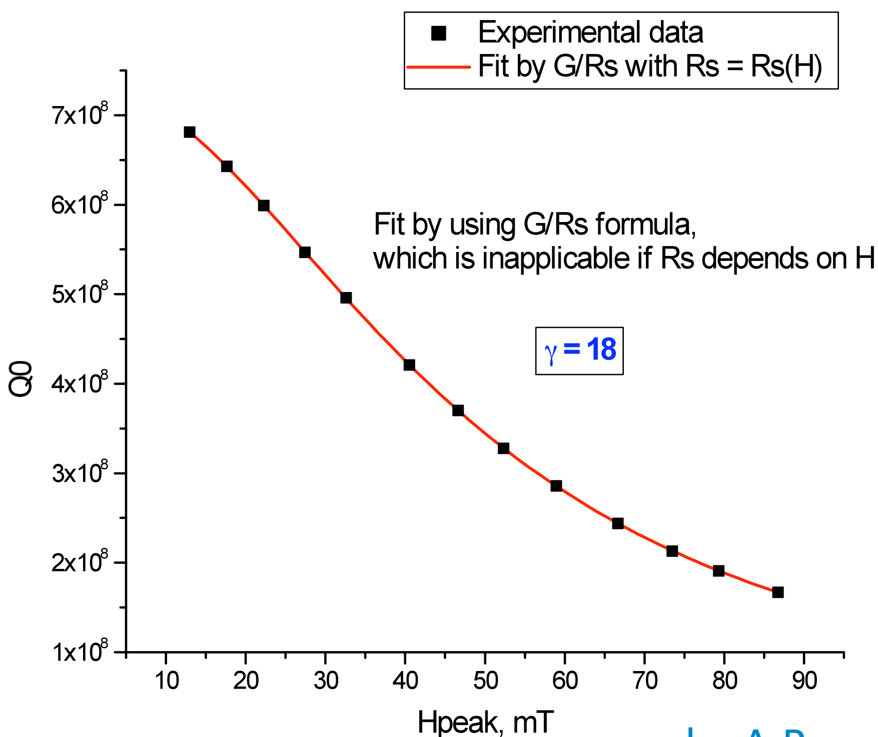
$$Q_0 = \frac{\omega \int\limits_{volume} \frac{1}{2}\mu_0 H^2 dv}{R_s(H) \int\limits_{surface} \frac{1}{2} H^2 ds} = \frac{G}{R_s}$$

If the goal is giving a rough estimate of the avg surface resistance then OK

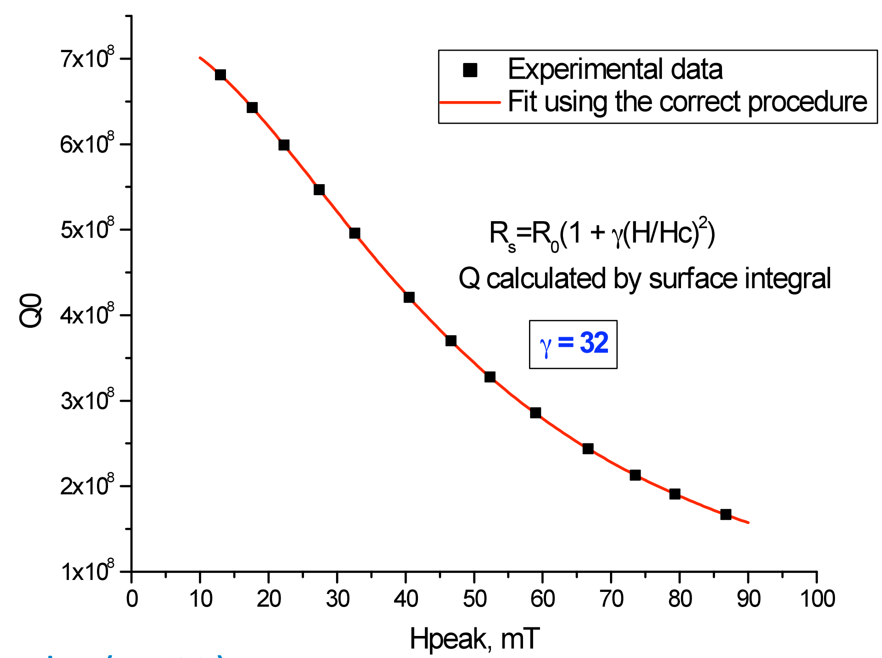
But if we try to understand the field dependence of Rs, it's meaningless to first assume Rs does not depend on H and then look for the (strong) H dependence.

Case study: low beta quarter wave 88 MHz

Incorrect procedure



Correct procedure



by A.Romanenko (FNAL)

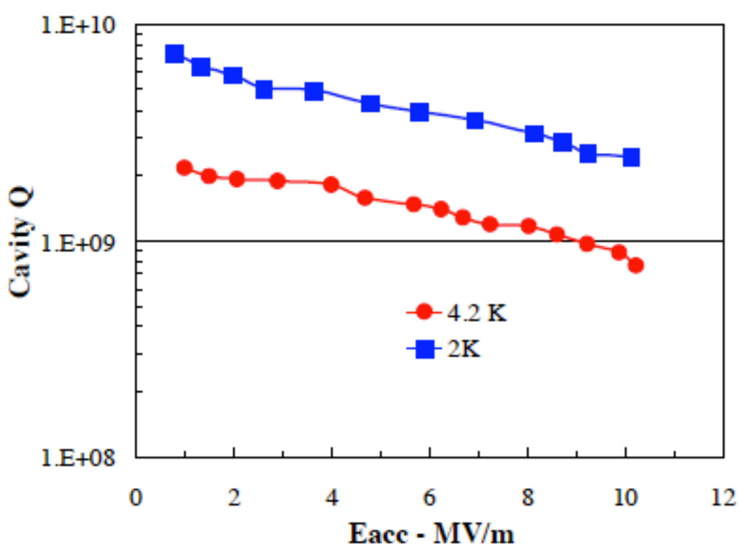
Ratio of the correct gamma to the “G/Rs” gamma for this geometry: 1.76

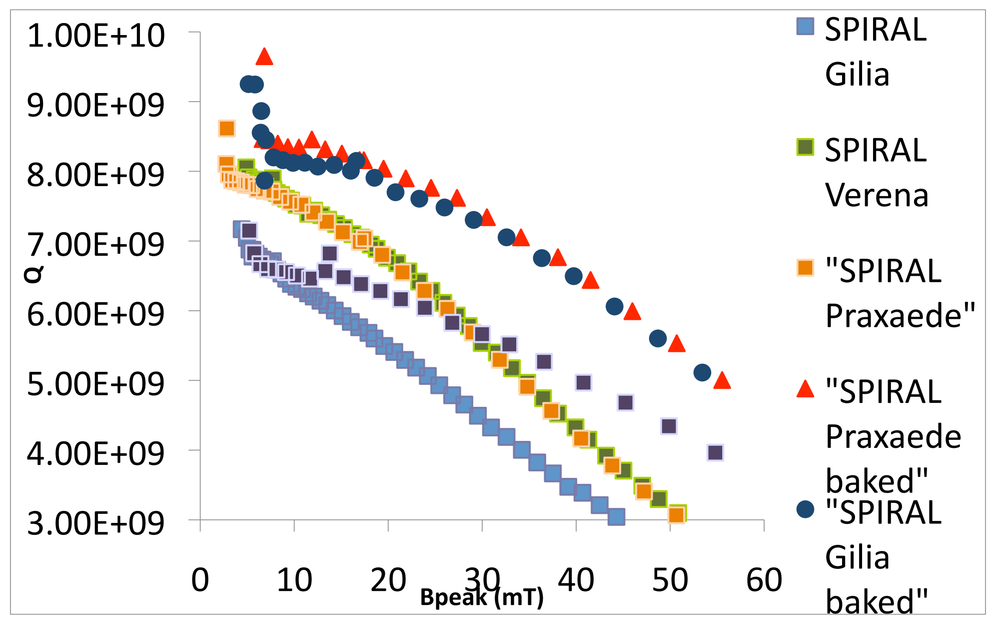
G/Rs summary

- Comparison within one fixed geometry between different treatments – qualitative trend – G/Rs values can be used
- Across different geometries – G/Rs is incorrect, only numerical surface integration should be used to extract Gammas and other Rs parameters
- Correction factors (GammaReal/GammaG_Rs)
  - Low beta quarter wave – 1.76
  - High beta elliptical – 1.27

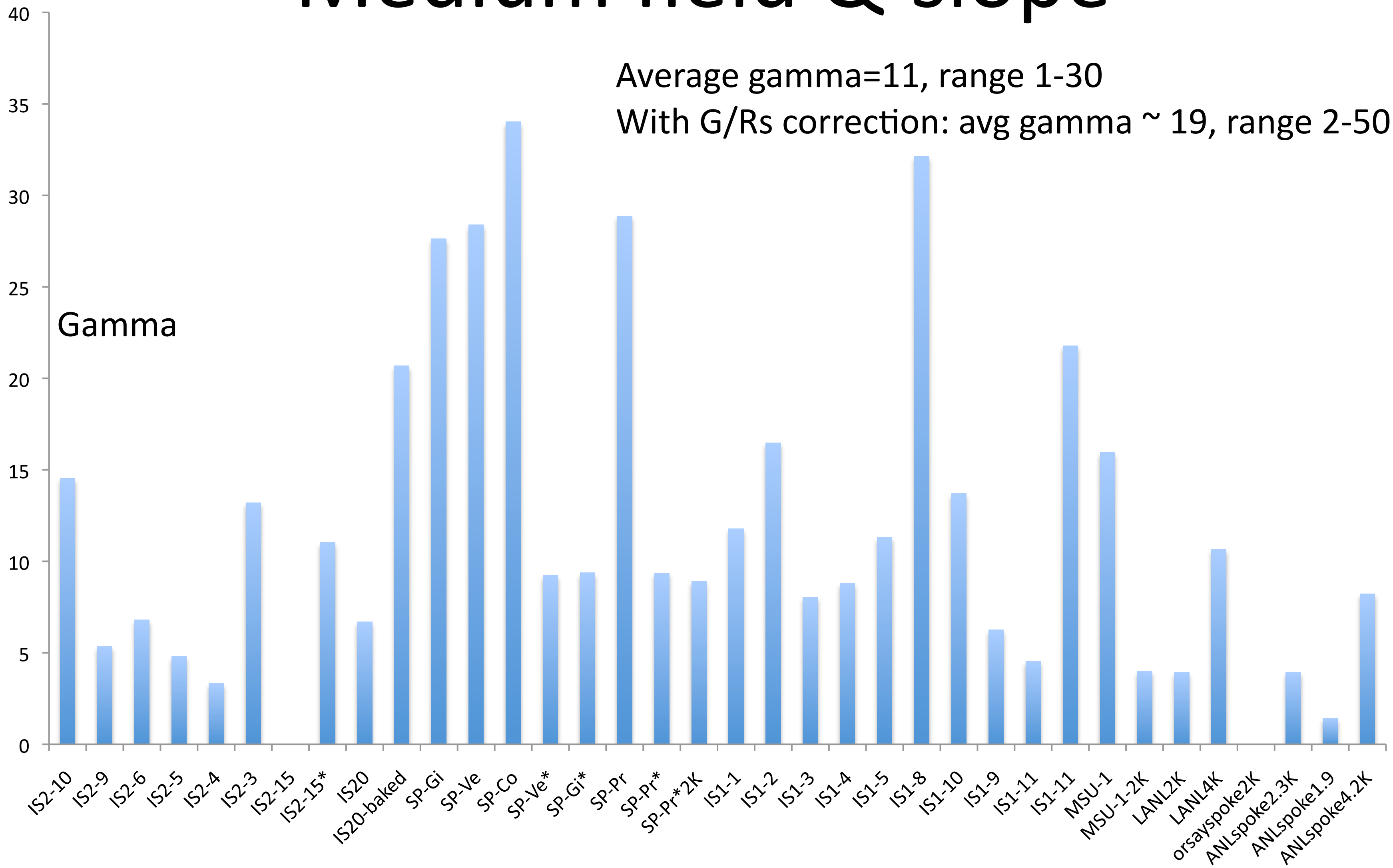
Low field Q-slope

- Low field Q-increase is never observed in low beta cavities
- Steeper (than mf) slope below 20-30 mT
- Effect more pronounced after baking

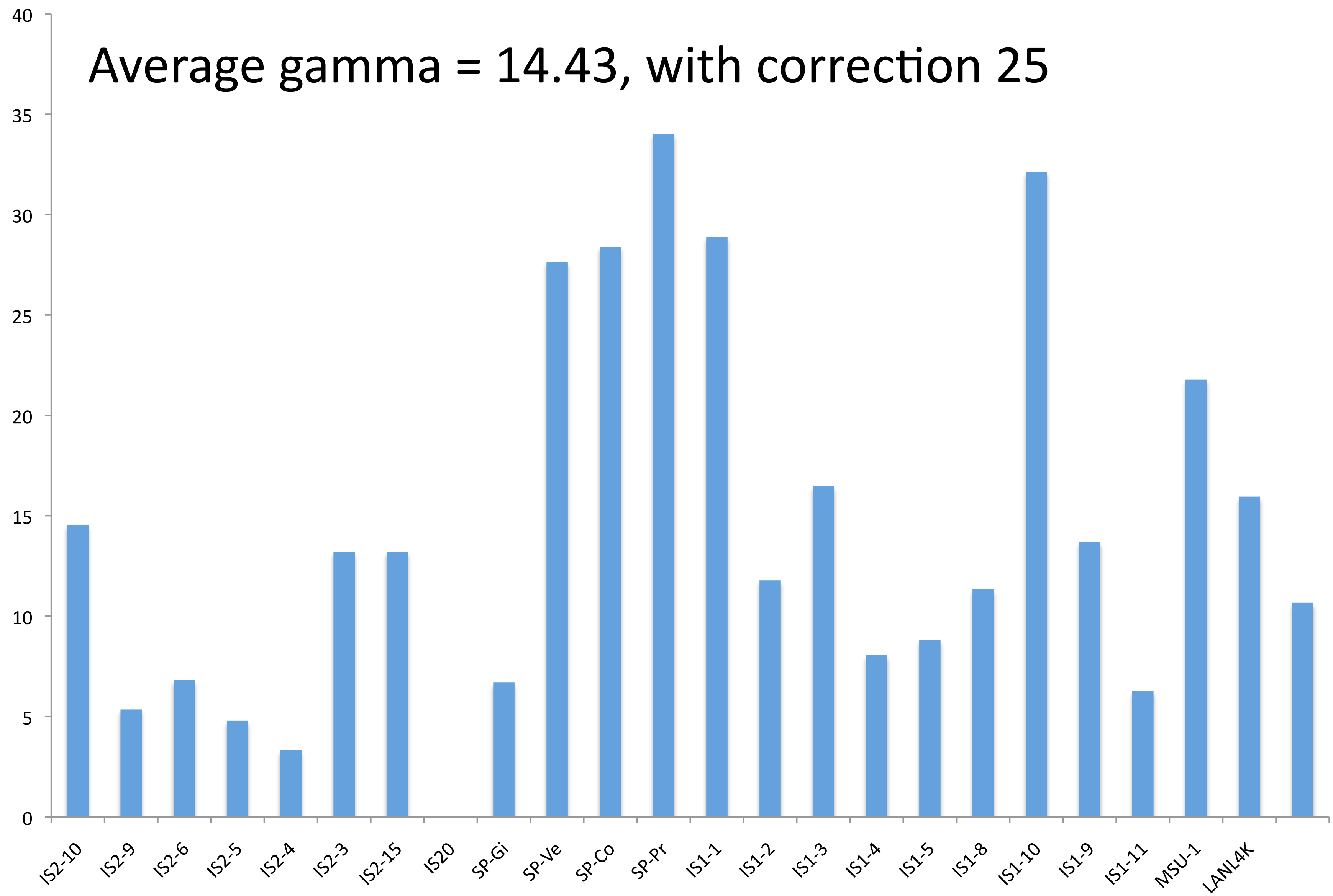




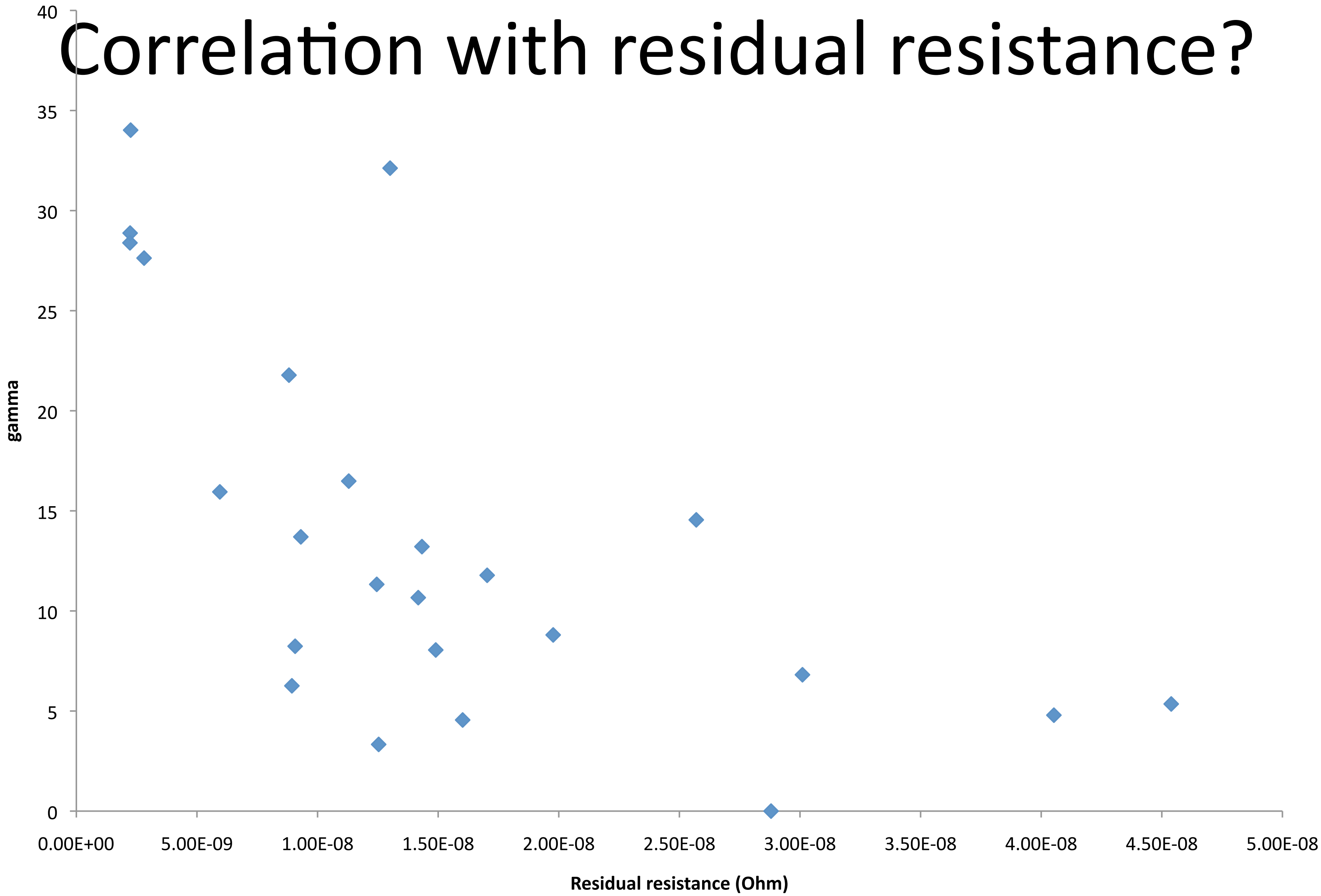
Medium field Q-slope



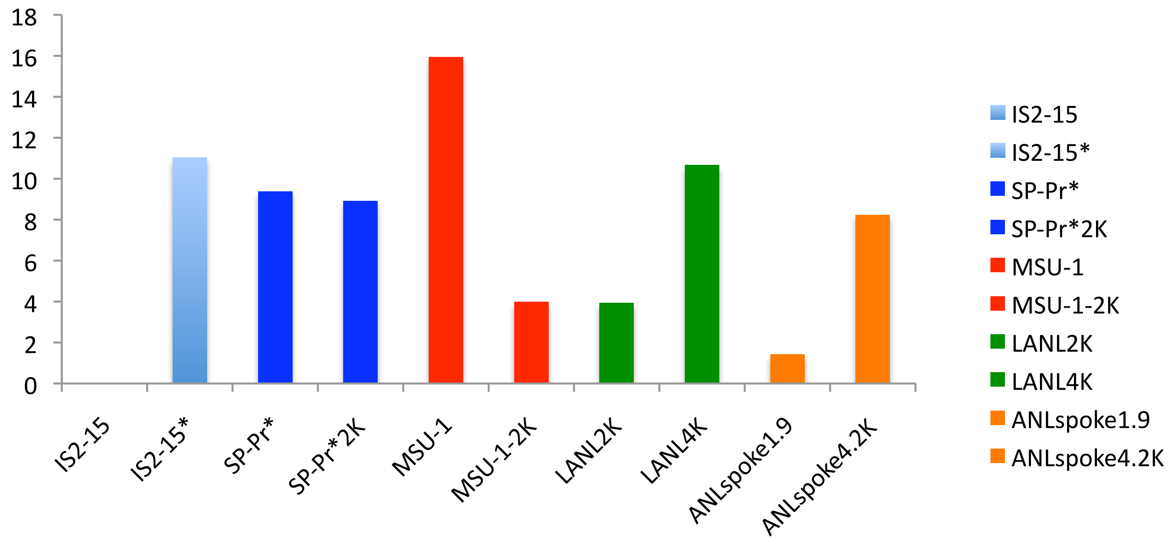
BCP, unbaked, 4.2K



Correlation with residual resistance?



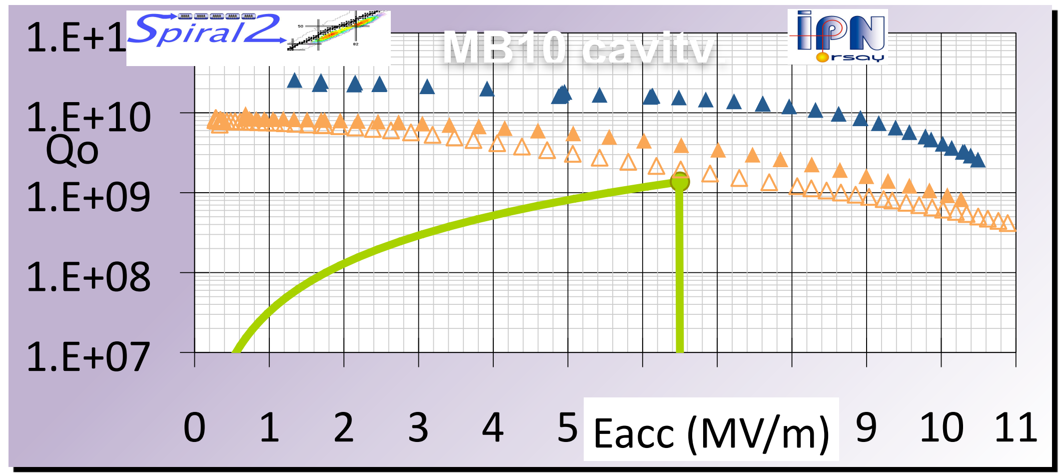
2K vs 4.2K



	Gamma @ 4.2K	Gamma @ 2K	Rlinear @ 4.2K	Rlinear @ 2K
ISAC2-cav15	11.033	0	1.96e-7	1.34e-7
Spiral-Praxaede	9.36	8.91	0	0
MSU-1	15.94	3.99	0	0
LANL-SS	10.66	3.92	0	0
ANL-TS	8.23	1.42	0	0

120C bake effect on MFQS

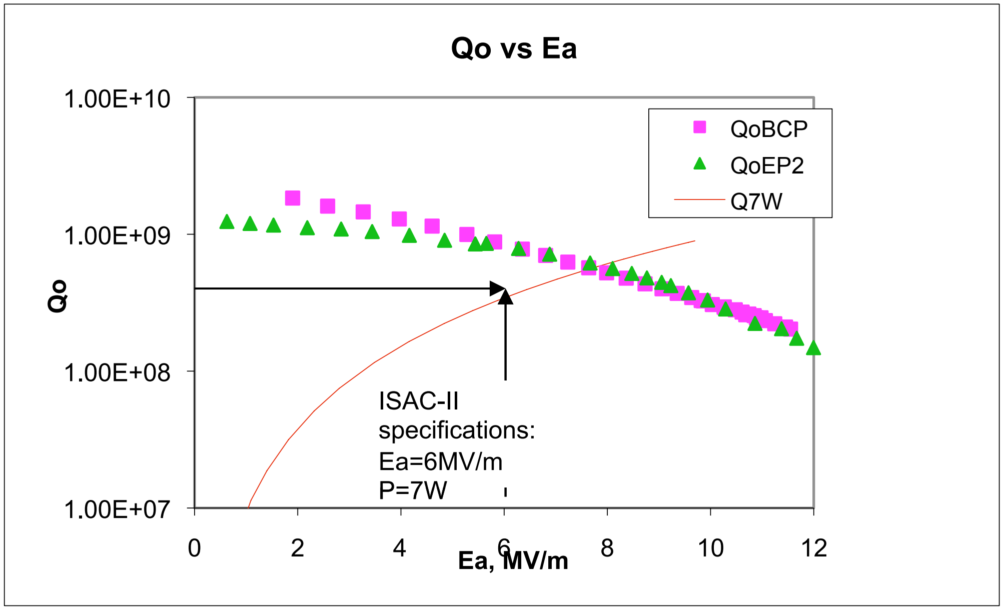
- 120C bake always improves significantly MFQS in SPIRAL cavities
- Preliminary results of studies at TRIUMF (D.Longuevergne, B.Laxdal, V.Zvyagintsev) on ISAC2 cavities show also improvement of MFQS with 120C bake



	Gamma before	Gamma after	Rlin before	Rlin after
SPIRAL	28.8	9.36	0	0
ISAC2	6.69	20.7	6.31e-7	4.17e-7

BCP vs EP

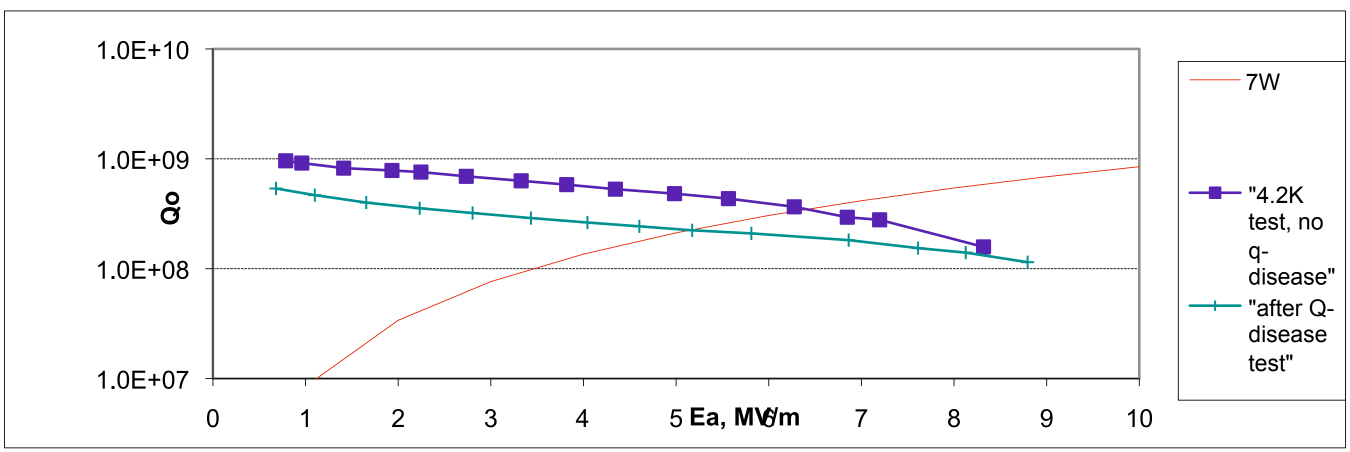
- Lower MFQS with EP than BCP in TRIUMF 106 MHz QWR
- Appearance of linear component after EP
- ANL spoke resonators also show lower gammas



	Gamma	Rlinear
ISAC2-cav11 EP	4.55	6.92e-9
ISAC2-cav11 BCP	21.77	0

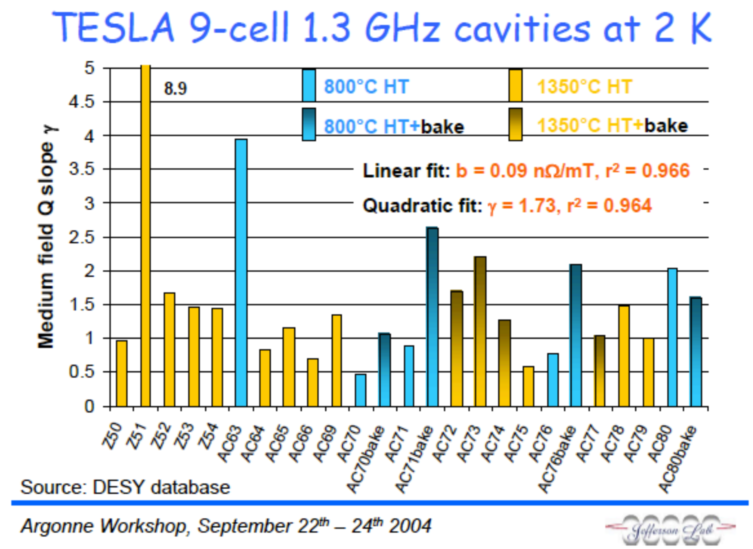
Hydrogen role on low beta MFQS

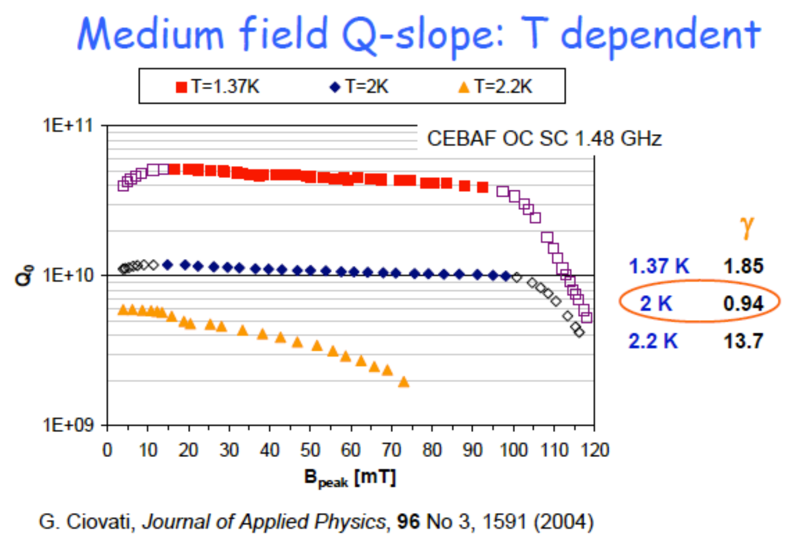
- Test at TRIUMF, look for correlation slope-hydrogen
- Several QW cavities tested after fast cooldown and after 1-2 hr at 100K (V.Zvyagintsev)
- Trend in slope-additional resistance from Q-disease test
- Also, the lowest gamma value (gamma~2)among analyzed low beta resonators (2K) is the degassed ANL 0.63 triple spoke
- However ANL TS 4.2K slope (gamma ~10) did not change significantly with degassing



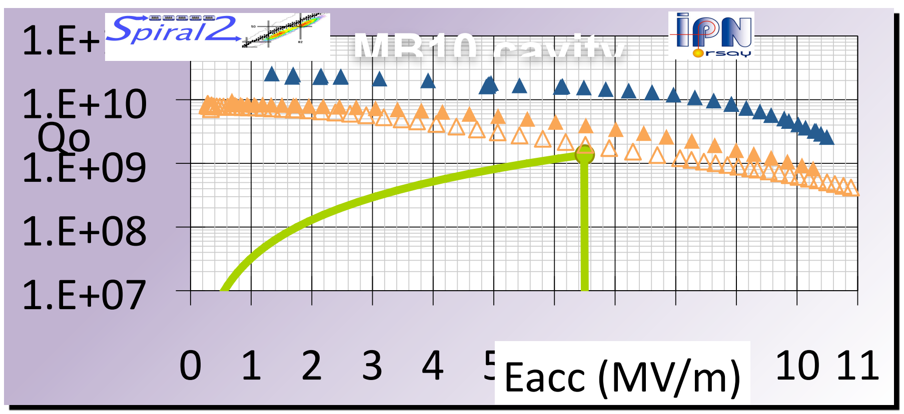
Comparisons MFQS low-high beta: 2K, 4.2K

- From this analysis 2K MFQS range ~ gamma from 2 to 15
- MFQS at 2K higher for low beta cavities
- Slope at 4.2K average around gamma ~ 25 for low beta, which is slightly higher than what observed in high beta (~20)

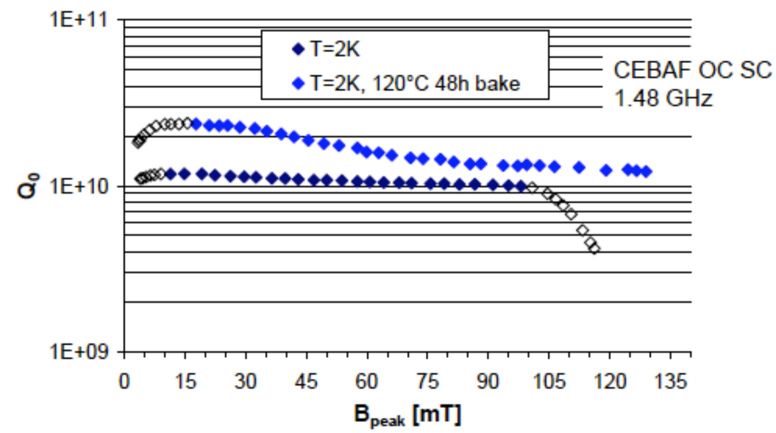




Comparison MFQS low-high beta: contradictory results 120C bake



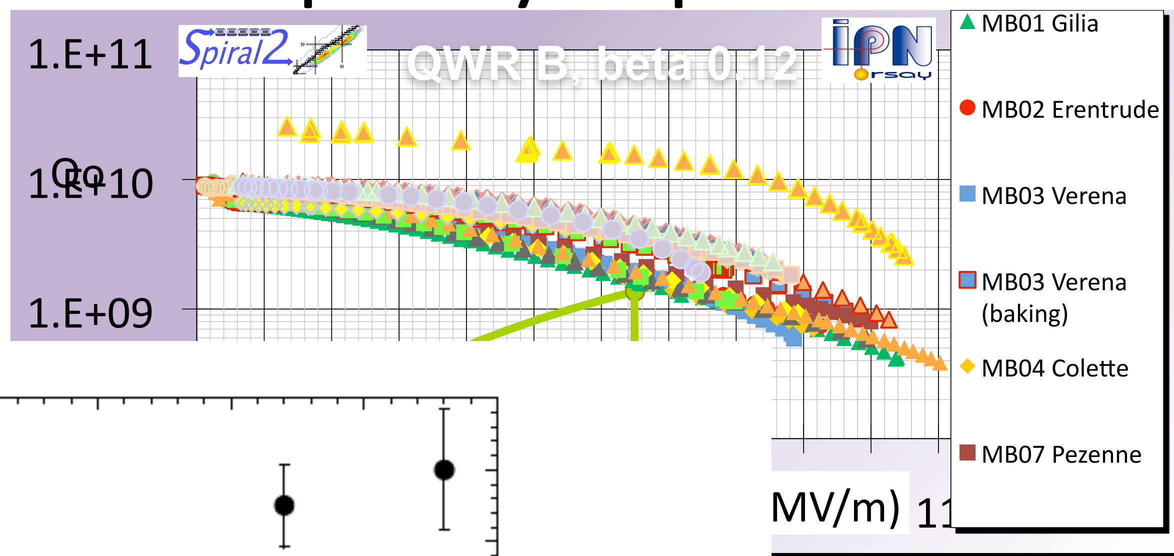
Medium field Q-slope: baking effect



- Increase of medium field Q-slope by baking
- Change from quadratic to linear R_s vs B_p dependence

HF onset and slope – frequency dependence

SPIRAL, ISAC2



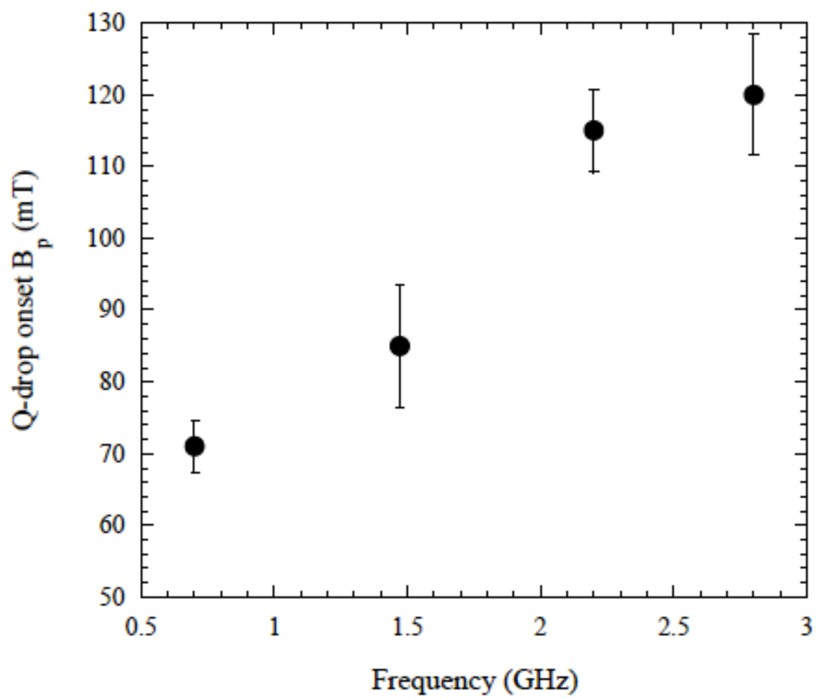
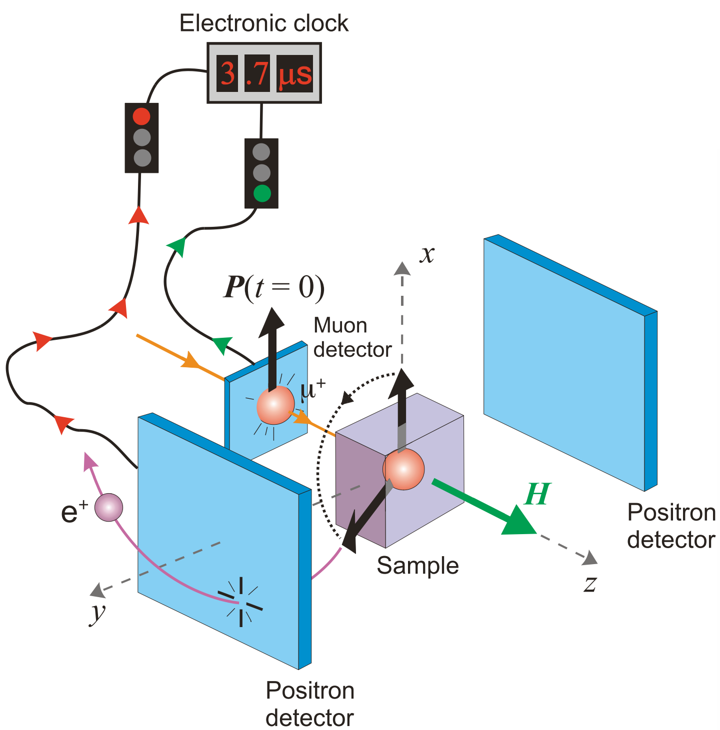


FIG. 102. Onset field of the high-field *Q*-drop as a function of frequency. The data point at 0.7 GHz is from [104], the one at 2.82 GHz is measured in the TE_{011} mode.

Cutout studies at TRIUMF: muSR



"Themes" in μSR

Muonium as light Hydrogen

(Mu = μ^+e^-) (H = p^+e^-)

- **Mu vs. H atom Chemistry:**
  - gases, liquids & solids
  - Best test of reaction rate theories.
  - Study "unobservable" H atom rxns.
  - Discover new radical species.
- **Mu vs. H in Semiconductors:**
  - Until recently, μ^+SR → **only** data on metastable H states in semiconductors!

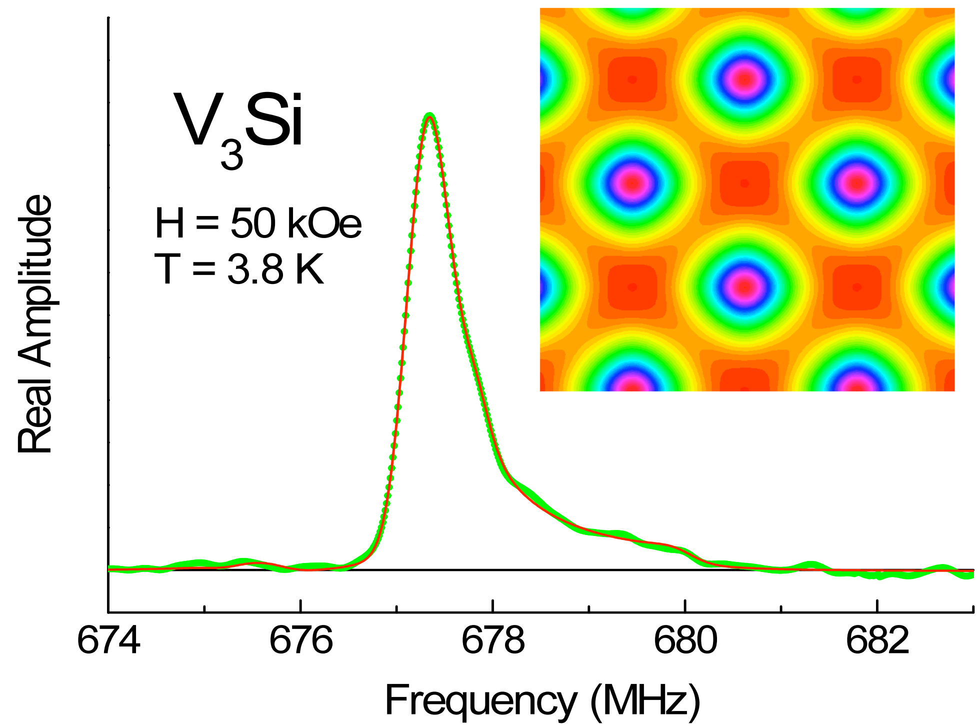
The Muon as a Probe

- **Probing Magnetism:** unequalled sensitivity
  - Local fields: electronic structure; ordering
  - Dynamics: electronic, nuclear spins
- **Probing Superconductivity:** (esp. HT_cSC)
  - Coexistence of SC & Magnetism
  - Magnetic Penetration Depth λ
  - Coherence Length ξ

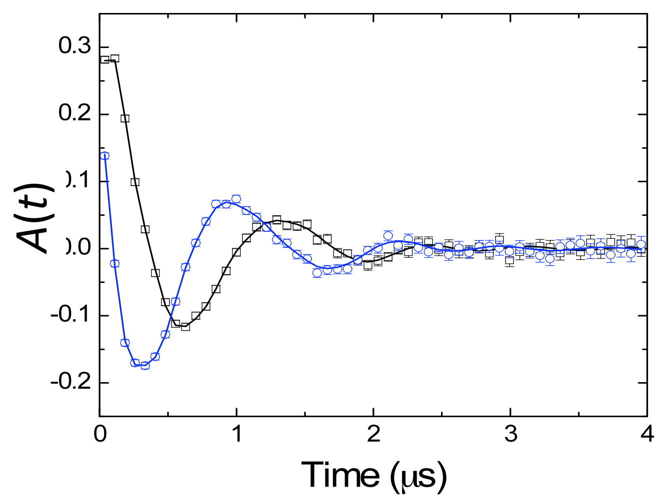
- **Quantum Diffusion:** μ^+ in metals (compare H^+); Mu in nonmetals (compare H).

Magnetic field distribution of a vortex lattice

Very sensitive local probe of magnetism, able to tell about magnetism that is localized in certain regions of the sample, and how much of the sample contains it.



Asymmetry spectrum plotted in a rotating reference frame



Fourier transform

RF losses due to fluxoids: of interest for MF and HFQS

- Two mechanisms for fluxoids in Nb:
  1. Trapped flux
  2. Penetration at sites with lower Hp (<Hc1)

- Two mechanisms of dissipation:
  1. Stationary normal region
  2. Oscillating fluxoid
     - Pinned
     - Depinned

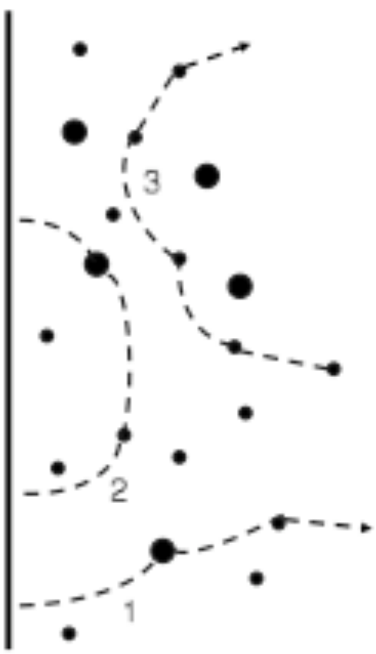
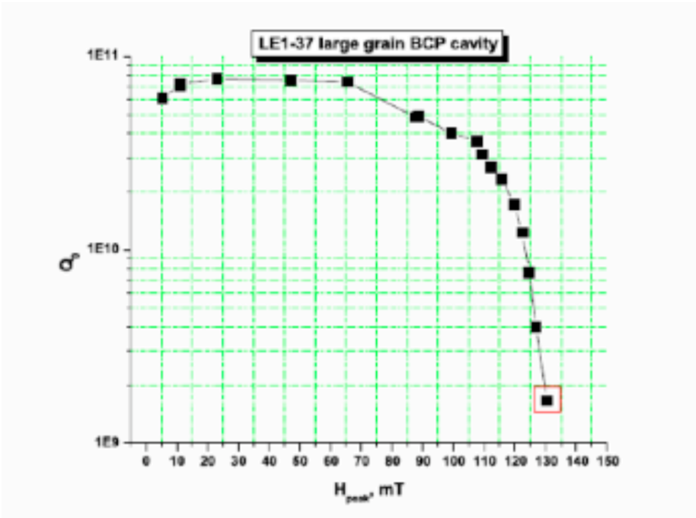
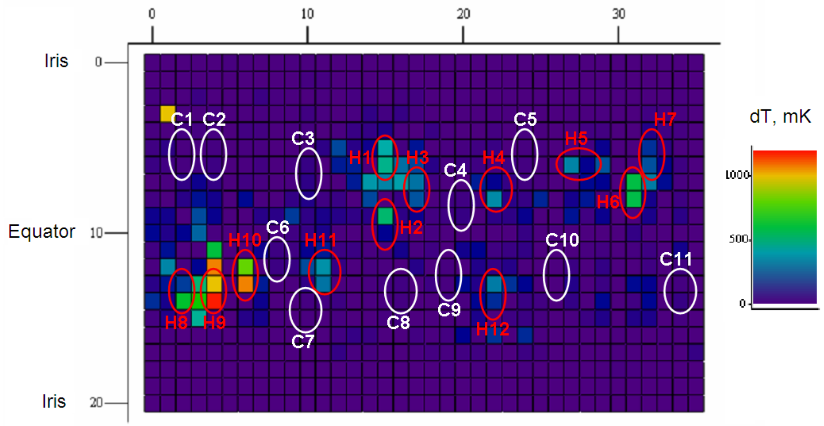


FIG. 17. Vortices (shown as dashed lines) trapped near the surface by pinning centers (black dots).

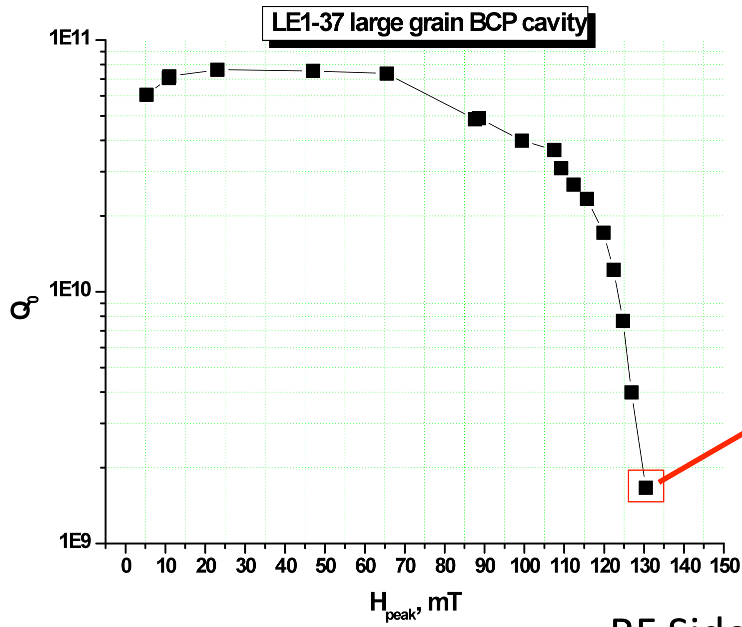
Hypothesis to test: HFQS

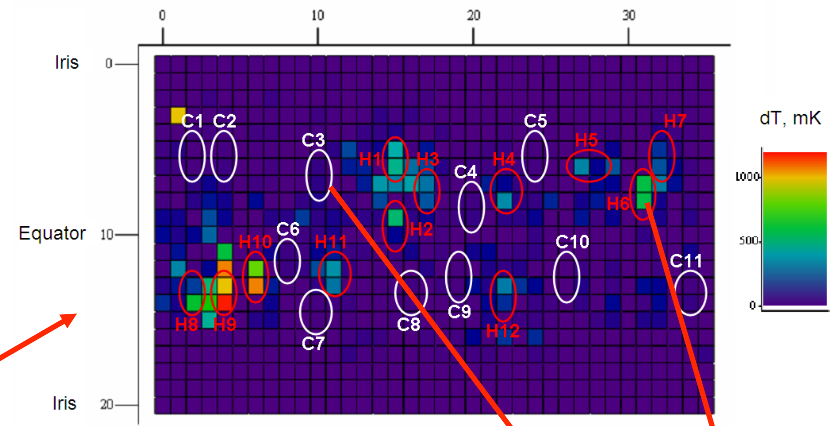
- Steep losses above 80-100mT due to early flux penetration
- Is the surface entering an intermediate mixed state?
- Correlate 'hot spots' cutout from cavities with areas of higher density of 'islands' in the mixed state

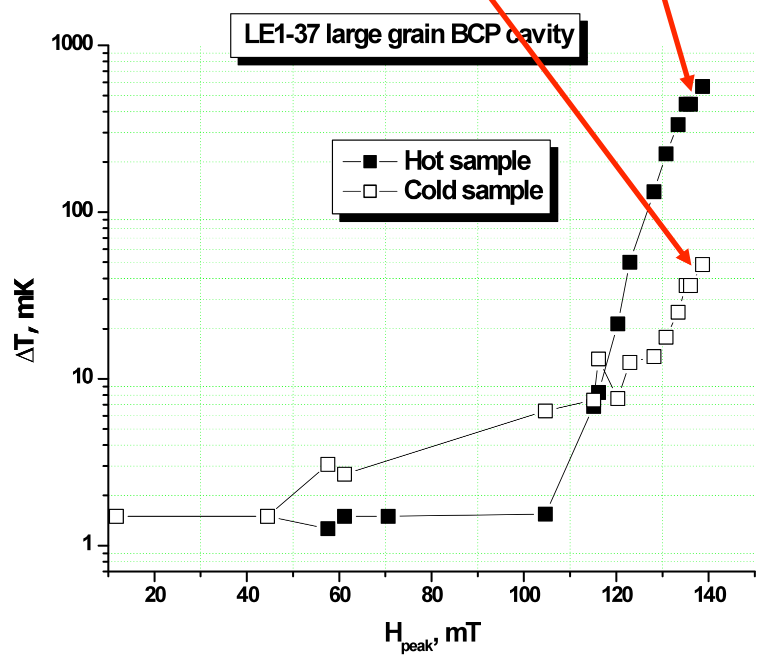




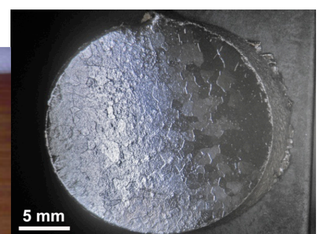
Samples to be used

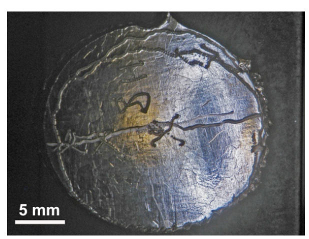






RF Side





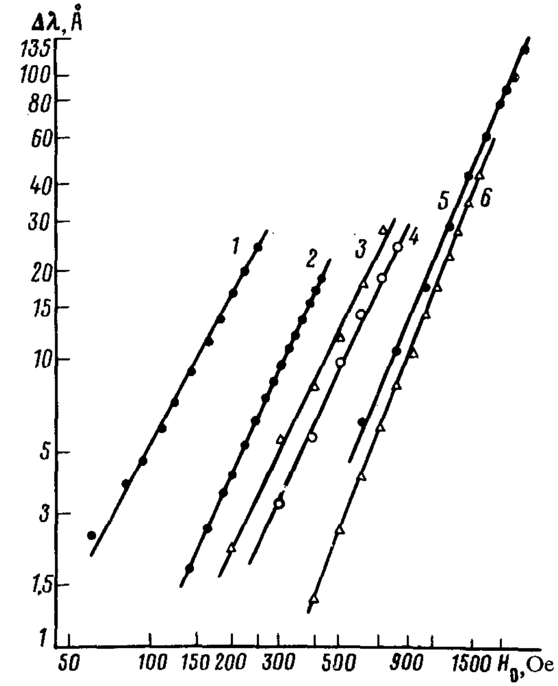
Outer Side

Description of the first experiment

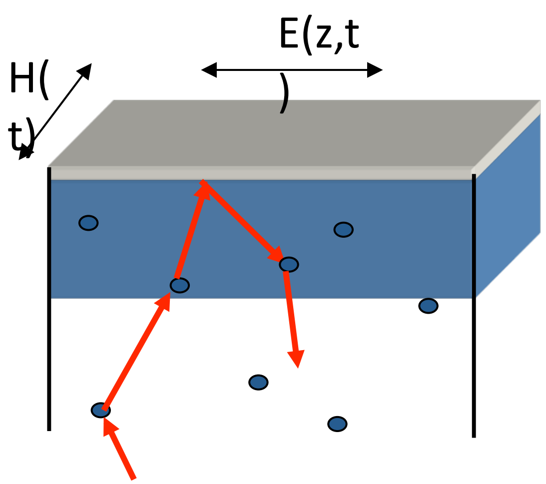
- Look for intermediate mixed state in hot spots cutout samples (~ cm^2 size, 3mm thick, interested only in RF side)
- Need for a local probe: muSR
- LAMPF spectrometer
- Field range 0-150 mT, Temperature range 1K-4.2K
- 5 samples:
  - Pristine Nb –from vendor
  - Hot/cold spot cutout from large grain cavity (before and after bake) – provided by Alexander Romanenko, Hasan Padamsee (Cornell)
- Beamtime approved: ~1 day per sample → 12 shifts, starting Oct 27th

Hypothesis to test: MFQS

- Field dependence of penetration depth
- Field dependent losses due to increased volume where dissipation occurs



Ermolov, Marchenko, Chizov, 1986



$$R_s \sim (\mu_0^2\omega^2\lambda^3\sigma_n\Delta/T)\exp(-\Delta/T)$$

$$R_s \propto \frac{\mu_0^2\omega^2\lambda^4\Delta n_0}{k_B T p_F}\left[\ln\left(\frac{\Delta}{\hbar\omega}\right)+C_0\right]\exp\left(-\frac{\Delta}{k_B T}\right)$$

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Field Dependence of the Vortex Core Size in a Multiband Superconductor

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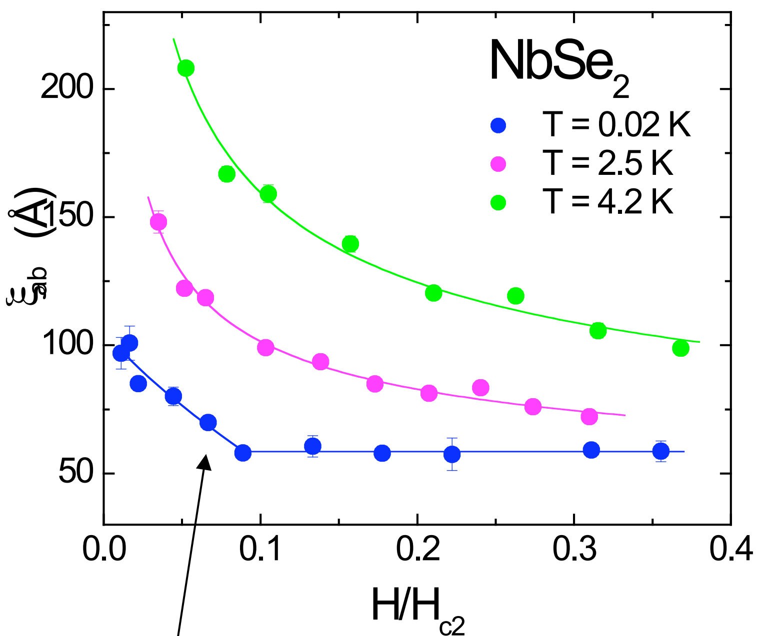
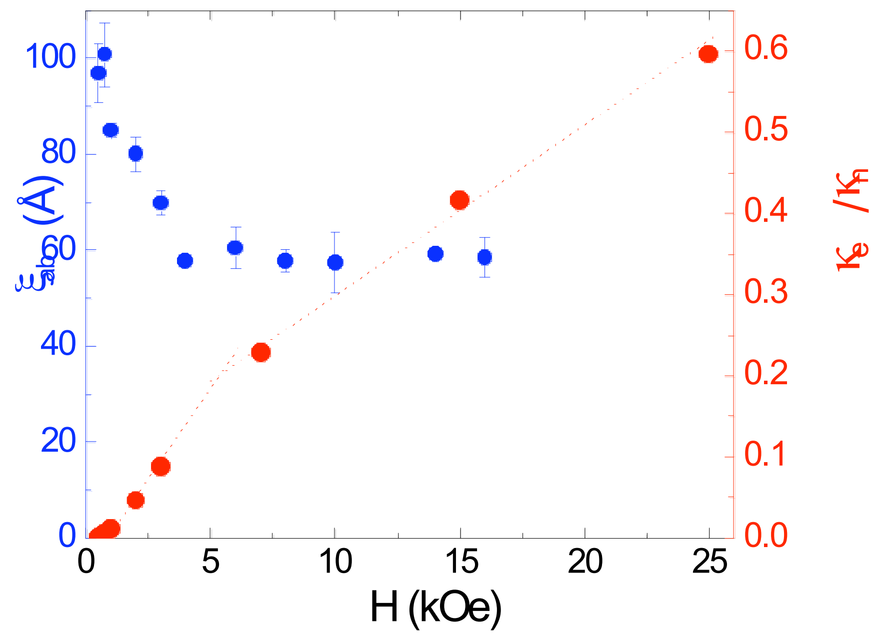
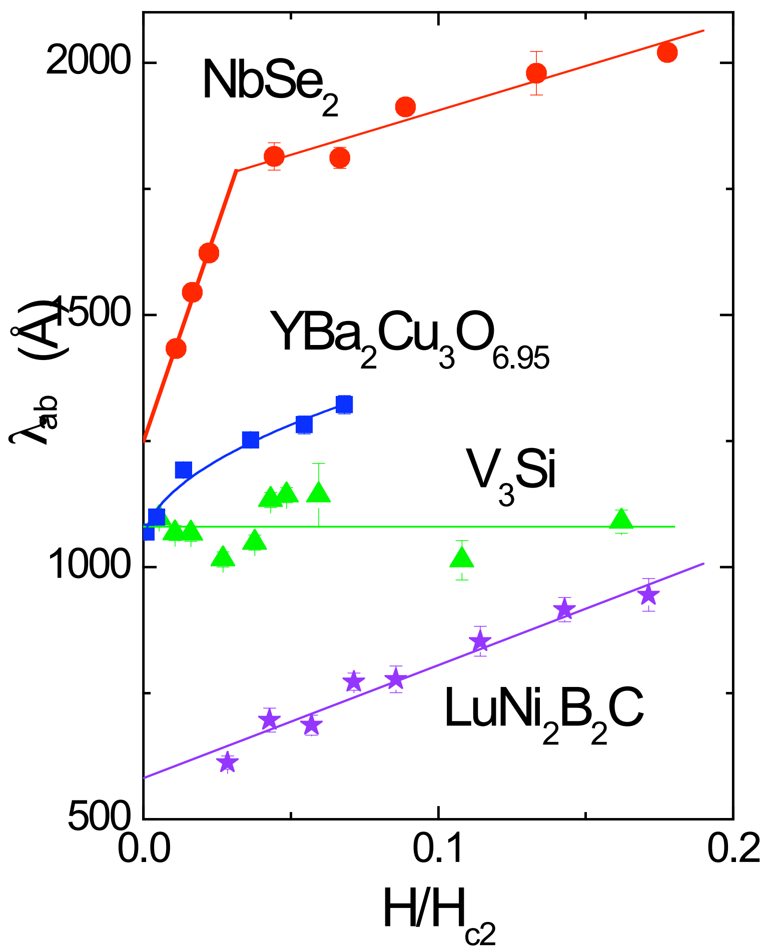




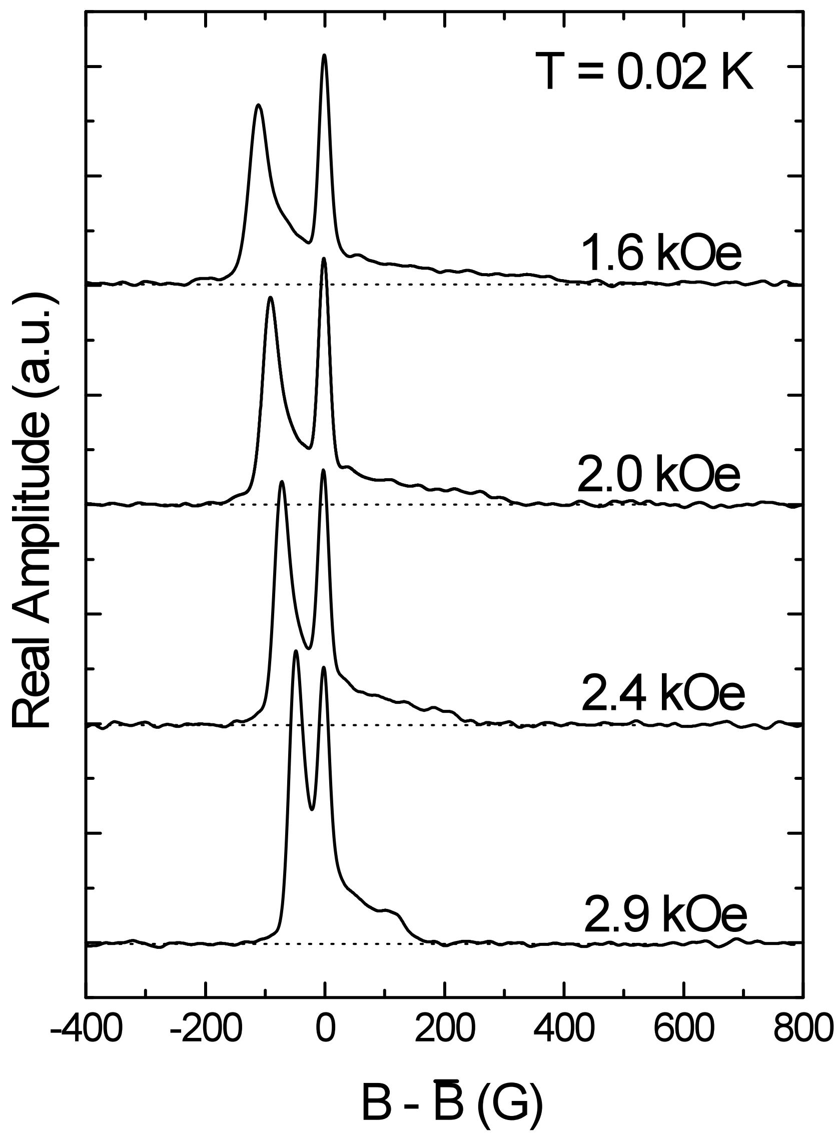
Freeze out thermal excitations of quasiparticle core states to reveal *multiband vortices*.

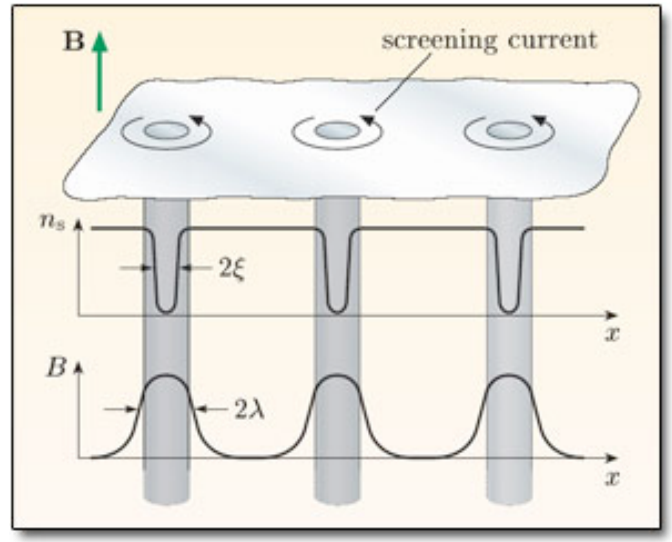
"Effective" Magnetic Penetration Depth: Magnetic Field Dependence

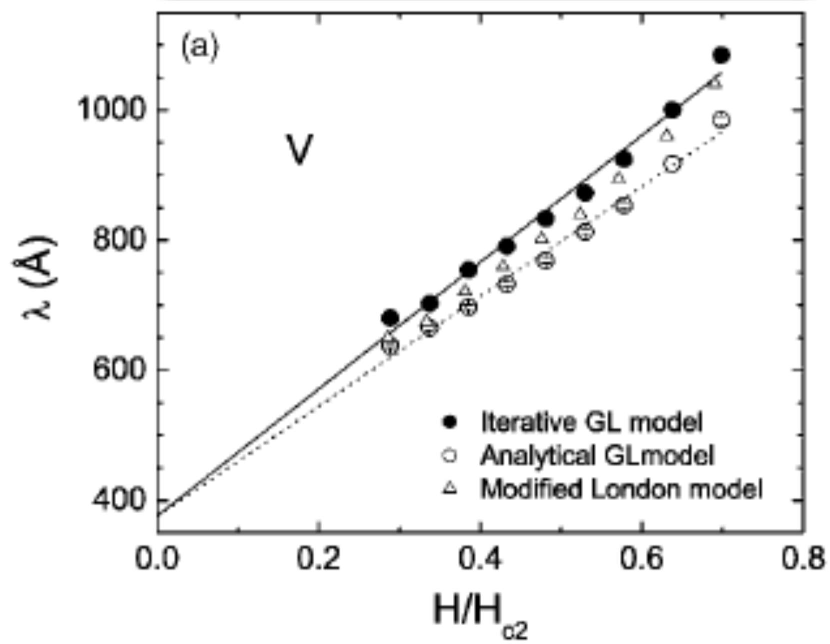


- V_3Si fully gapped
- $LuNi_2B_2C$ anisotropic gap
- $YBa_2Cu_3O_{6.95}$ $d_{x^2-y^2}$-wave gap
- $NbSe_2$ multiband

Pure Vanadium (*marginal type-II*)







Laulajainen, Callaghan, Kaiser & Sonier PRB 74, 054511 (2006)

Description of the second experiment

- Determine the field dependence of the effective penetration depth (and vortex core size) in the vortex and intermediate mixed states. Will do this at several temperatures to investigate the possibility of two SC gaps.
- Take advantage of muSR unique software for measurements of the vortex lattice in a marginal type-II
- TF-muSR, dilution refrigerator
- Pristine single crystal sample
- Beamtime approved: 12 shifts

Conclusions

- HFQS:
  - well defined problem
  - one physical underlying mechanism
  - unsolved
  - muSR experiment at TRIUMF to confirm or rule out role of early flux penetration
- MFQS:
  - several contributors, both local and global
  - To be found in both microscopic and macroscopic parameters
  - Hydrogen plays a role at low beta, need for more degassing studies (planned at TRIUMF)
  - Need for diagnostic tools like thermometry and more cutout studies
  - some planned at TRIUMF again with muSR