HOW IS FLUX EXPULSION AFFECTED BY GEOMETRY: EXPERIMENTAL EVIDENCE AND MODEL

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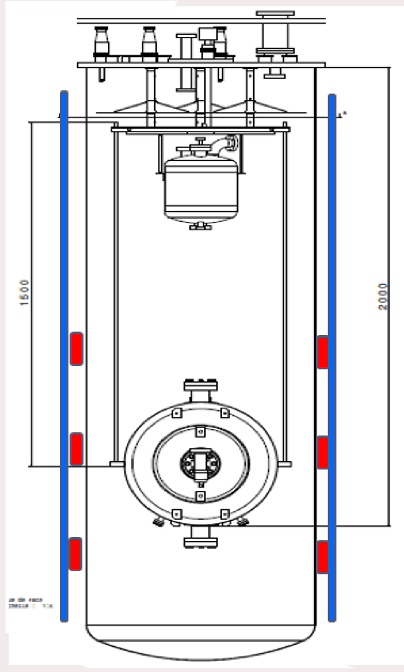
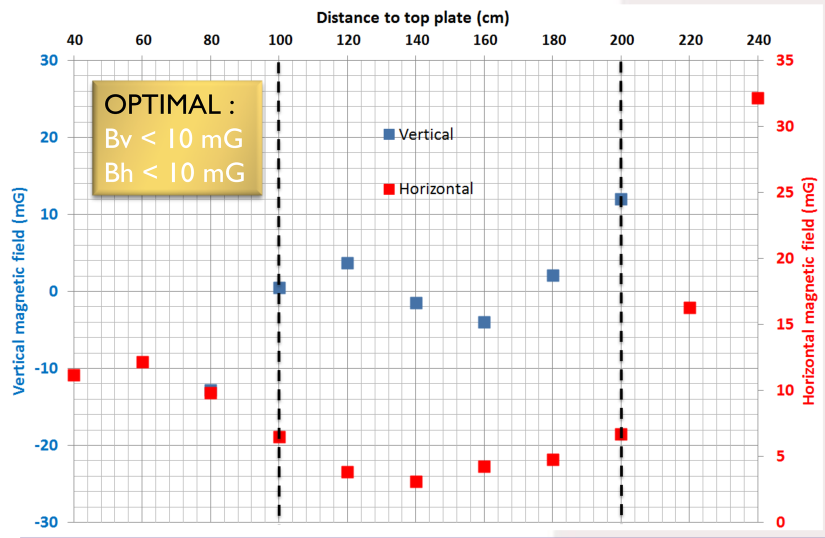
Abstract:

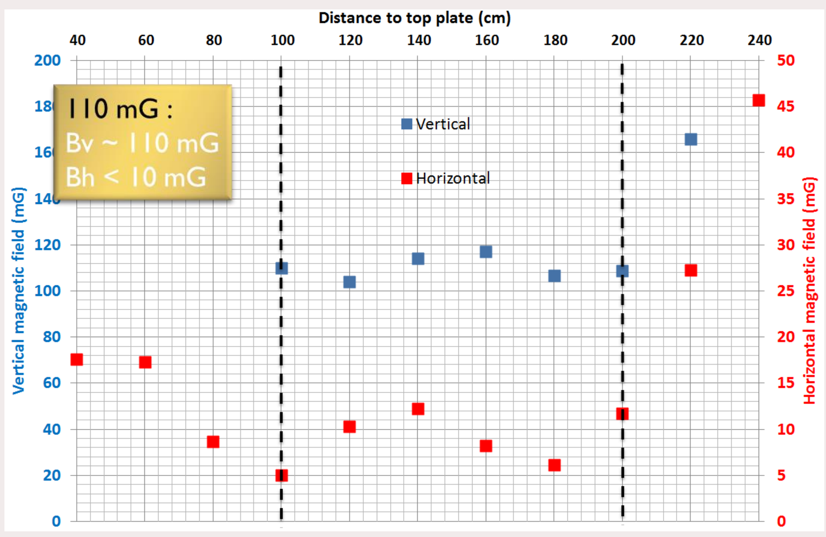
Measurements of magnetic sensitivity to trapped flux on several type of cavity geometries have been performed at IPNO showing a clear geometrical effect. Magnetic sensitivity depends not only on material quality but also on the cavity geometry and on the residual magnetic field orientation. A presentation of experimental data will be done. These will be as well compared to the theoretical magnetic sensitivities calculated thanks to a simple Labview routine

Experimental set up and results

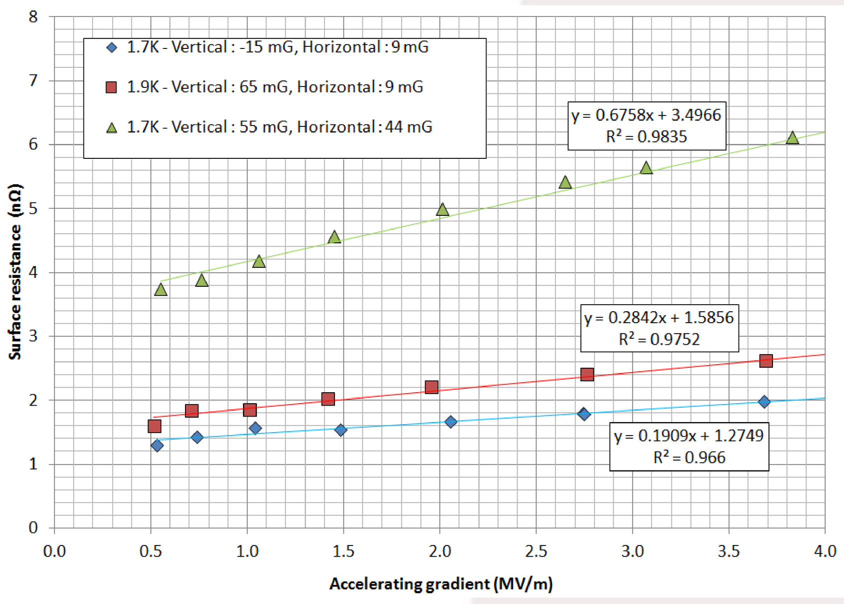


- Passive shielding : 0.6 mm mu-metal around cryostat : B < 25 mG
- Active shielding : 3 coils inside mu-metal sheets
  - Optimal residual magnetic field B<10 mG
  - Can apply vertical and uniform magnetic field up to 110 mT.
  - The residual horizontal component stays below 10 mG.
- Magnetic sensors : fluxgate from Bartington (MAG01-H with 9 Type G sensors) [1]
- Theoretical formula [2] : $S_{mag} = \frac{R_{mag}}{H_{res}} = \sqrt{\frac{\omega \cdot \mu_0}{2 \cdot \sigma_n \cdot RRR}} \cdot \frac{1}{H_{c2}}$

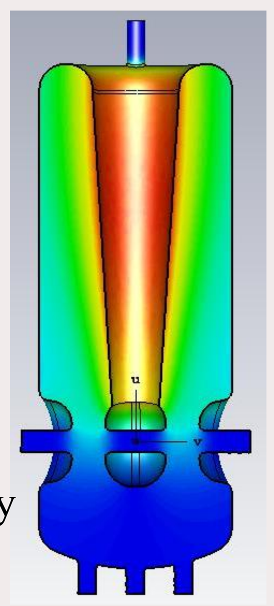




QWR (SPIRAL2) : S_{mag}= 0.056 nΩ/mG @ 88 MHz, @ 1.7K



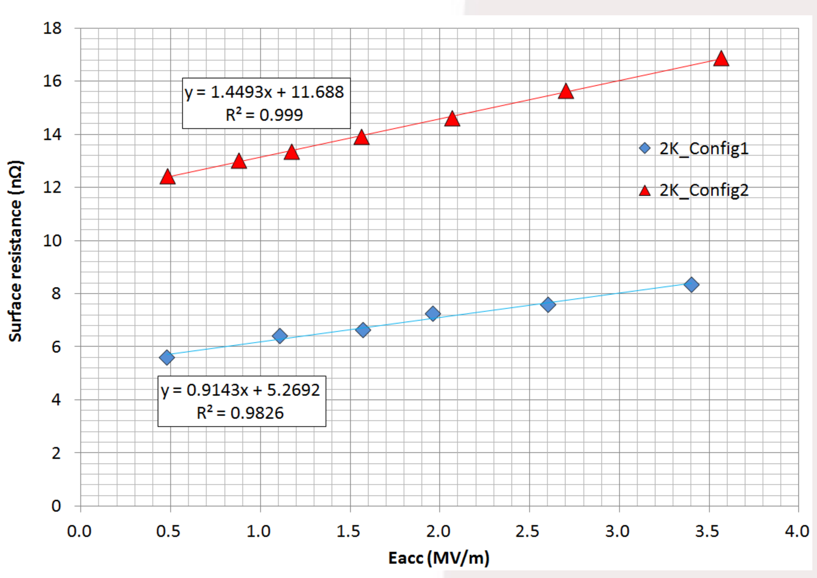
SPIRAL2 QWR [3]
- ✓ F_0 = 88 MHz
- ✓ Bpk/Eacc = 10.5 mT/MV/m
- ✓ r/Q = 515 Ω
- ✓ G = 33 Ω



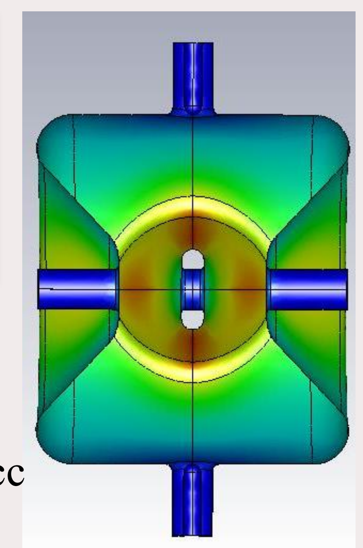
Measured sensitivities:

S_H = 0.006 nΩ/mG
S_V = 0.05 nΩ/mG
- Strong depence with geometry
- Linear dependence with Eacc

S-Spoke (MYRRHA) : S_{mag}= 0.12 nΩ/mG @ 352 MHz, @ 2K



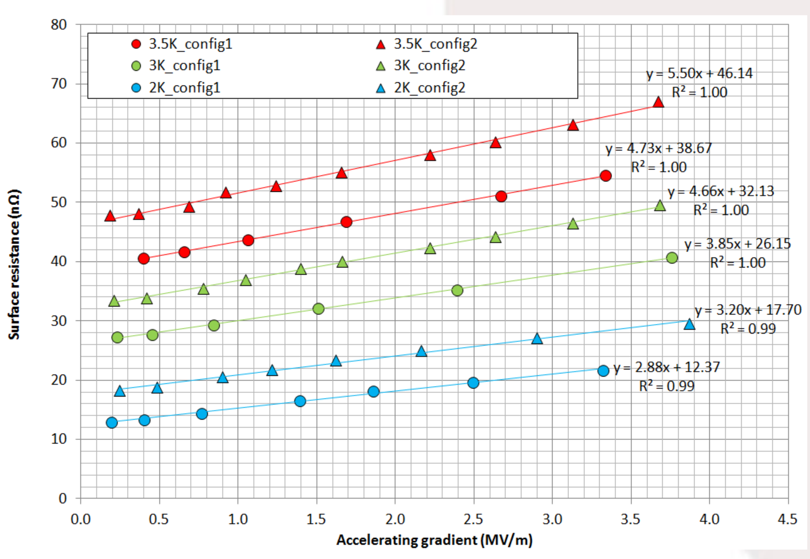
MYRRHA Spoke [4]
- ✓ F_0 = 352 MHz
- ✓ Bpk/Eacc = 7.3 mT/MV/m
- ✓ r/Q = 217 Ω
- ✓ G = 109 Ω



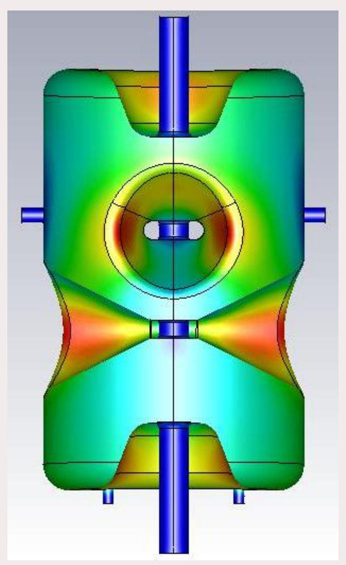
Measured sensitivities:

S_V = 0.06 nΩ/mG
- Linear dependence with Eacc

D-Spoke (ESS) : S_{mag}= 0.12 nΩ/mG @ 352 MHz, @ 2K



ESS Spoke [5]
- ✓ F_0 = 352 MHz
- ✓ Bpk/Eacc = 6.9 mT/MV/m
- ✓ r/Q = 426 Ω
- ✓ G = 130 Ω

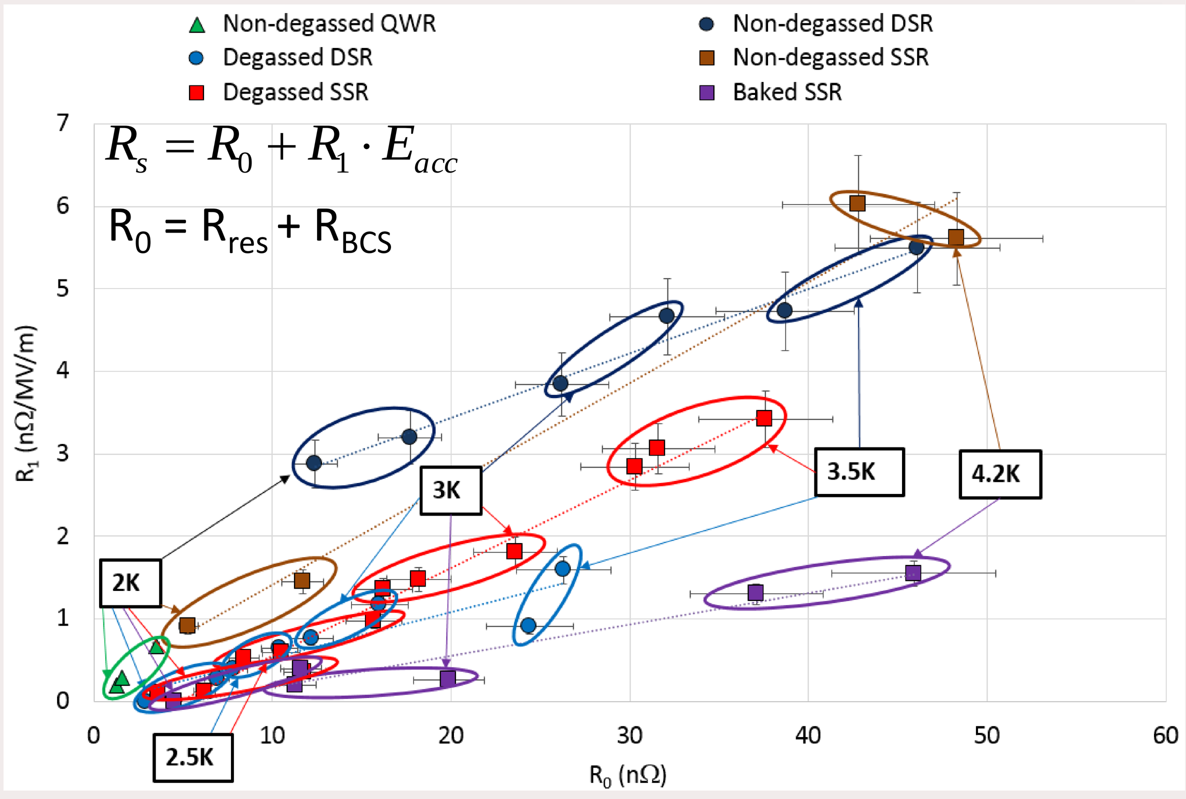


Measured sensitivities:

S_H = 0.06 nΩ/mG
- Linear dependence with Eacc

Analysis of results :

- From Spiral2 QWR measurement : The difference between the vertical and horizontal sensitivities suggest a strong geometrical dependence.
- Real sensitivity is consistently lower than theoretical sensitivity.
- Slow (~ 20 mK/s with thermal gradient <1K) and fast (~100 mK/s with thermal gradient >30K) show different magnetic field step (slow : ΔB~10mG, fast : ΔB~30mG) but no difference is observed on Qo. [4]
- The more magnetic field is trapped, the stronger the linear dependence of the surface resistance with accelerating gradient is. In agreement with literature [6]
- The magnetic sensitivity is temperature dependent. In agreement with literature [7]



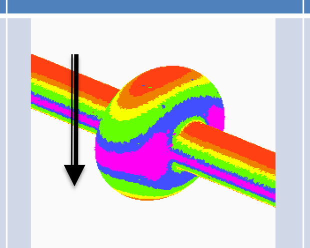
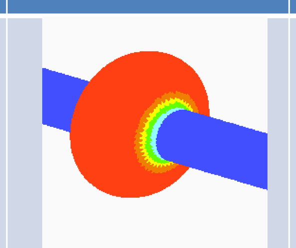
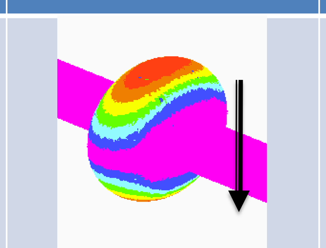
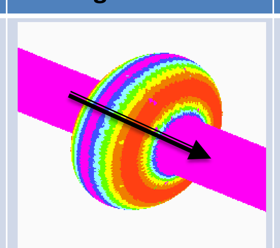
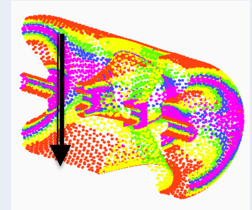
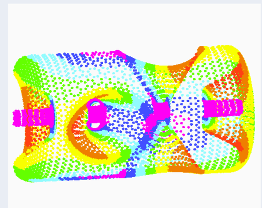
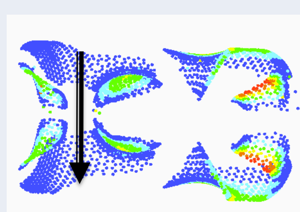
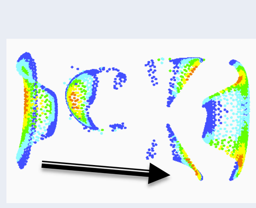
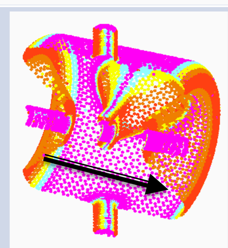
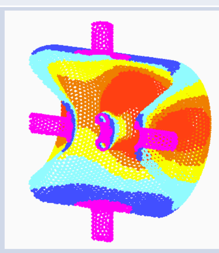
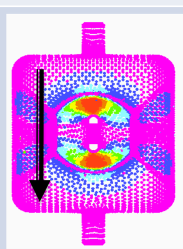
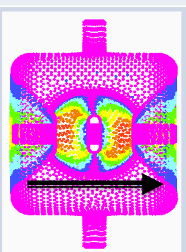
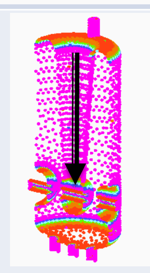
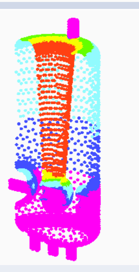
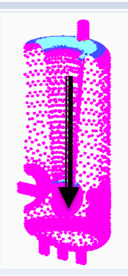
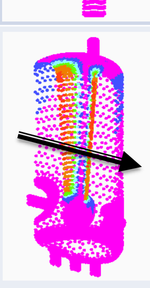
- Marker encircled together are done at the same temperature but with different external magnetic field applied
- R_1 is proportionnal to R_0 and is increased not only by flux trapping but also when temperature is increased
- Heat treatments (hydrogen degassing and 120°C baking) decreases field dependence.

Geometrical model and hypothesis:

- Only normal component of residual magnetic field is trapped [2,8].
- The external residual magnetic field is fully trapped during transition
- How to evaluate the local magnetic field sensitivity all over the geometry :

(1) : Evaluation of the real trapped flux and calculation of additional resistance R_{mag}
(2) : Evaluation of the additional local power dissipation
=> trapped flux induces additional losses only in RF magnetic regions
(3) : Evaluation of overal sensitivity

$$(1): \quad R_{mag} = R_n(f,T) \cdot \frac{H_\perp}{2 \cdot H_{c2}(T)} \qquad (3): \quad S_{mag} = \frac{\iint_S R_{mag} \cdot H_{RF}^2 \cdot dS}{H_{ext} \cdot \iint H_{RF}^2 \cdot dS}$$

Sensitivities to vertical field	Trapped flux regions	RF surface currents	Sensitive regions to vertical magnetic field	Sensitive regions to longitudinal magnetic field	Calculated sensitivities (nΩ/mG)
1.3 GHz elliptical cavity					@ 2K $S_{théo}$ = 0.22 S_{Vert} = 0.09 S_{long} = 0.14
352 MHz ESS Spoke					@ 2K $S_{théo}$ = 0.11 S_{Vert} = 0.06 S_{long} = 0.055
352 MHz MYRRHA Spoke					@ 2K $S_{théo}$ = 0.11 S_{Vert} = 0.05 S_{long} = 0.06
88 MHz SPIRAL2 QWR					@ 4.2K $S_{théo}$ = 0.08 S_{Vert} = 0.01 S_{long} = 0.05

nΩ/mG		Transverse sensitivity	Beam axis sensitivity	Vertical sensitivity	
SPIRAL2 QWR @ 4.2K @ 88 MHz	Calculated	0.048	0.048	0.011	Theoretical 0.08 nΩ/mG
	Measured	0.05		0.006	
	Error (%)	4 (-38)		-45 (-93)	
MYRRHA SPOKE @ 2K @352 MHz	Calculated	0.061	0.062	0.047	Theoretical 0.12 nΩ/mG
	Measured	[redacted]	[redacted]	0.043	
	Error (%)	[redacted]	[redacted]	-8.5 (-64)	
ESS SPOKE @ 2K @352 MHz	Calculated	0.057	0.055	0.057	Theoretical 0.12 nΩ/mG
	Measured	[redacted]	0.06	[redacted]	
	Error (%)	[redacted]	9 (-50)	[redacted]	

Error : relative error between measurement and calculations
(Error) : relative error between measurement and theoretical value

References:

[1]: https://www.bartington.com/
[2]: C. Vallet, "Etude de la dissipation dans les supraconducteurs en régime haute fréquence", PhD thesis, CEA Saclay, 1994.
[3]: C. Marchand et al., "Performances of Spiral2 Low and High Beta Cryomodules", WEBA04, Proceedings of the 17th International Conference on RF Superconductivity, SRF2015, Whistler, Canada, 2015.
[4]: D. Longuevergne et al., "Performances of the Two First Single Spoke Prototypes for the MYRRHA Project", Proceedings of the 28th Linear Accelerator Conference, LINAC16, East Lansing, USA, 2016.
[5]: P. Duchesne et al., "Design of the 352 MHz, Beta 0.50, Double-Dpoke Cavity for ESS", FRIOC01, Proceedings of the 16th International Conference on RF Superconductivity, SRF2013, Paris, France, 2013.
[6]: A. Miyazaki et al., "Two different origins of the Q-slope problem in superconducting niobium film cavities for a heavy ion accelerator at CERN, arXiv:1812.04658v1.
[7]: M. Ono, "Magnetic field effects on superconducting cavities", Proceedings of the workshop on RF Superconductivity, SRF99, Santa Fe, USA, 1999.
[8]: S. Candia et al., "Angular dependence of the magnetization of isotropic superconductors: which is the vortex direction ?", Supercond. Sci. Technol. 12 (1999) 192–198.

Conclusion & perspectives:

Flux trapping measurements done at IPNO on several type of resonators (QWR, Spoke) are revealing very clearly a strong geometrical dependence of the sensitivity to magnetic flux trapping. The real sensitivity, evaluated indirectly and globally by RF power measurements, is consistently lower than the theoretical sensitivity regardless the quality and history of the Niobium material. Assuming that only the normal component of the residual magnetic field is trapped during the superconducting transition appears to be a reasonable hypothesis and verified in [8]. A very good agreement between calculated and measured sensitivities is obtained when geometrical corrections are applied thanks to the model presented here. Moreover, a clear linear correlation is measured between the "zero field" surface resistance (R_0) and the field dependent resistance (R_1) and is significantly affected by surface and heat treatments. Even though R_1 is increasing with the amount of trapped flux, this linear dependence doesn't seem to be caused directly by trapped flux as even temperature make it rise.