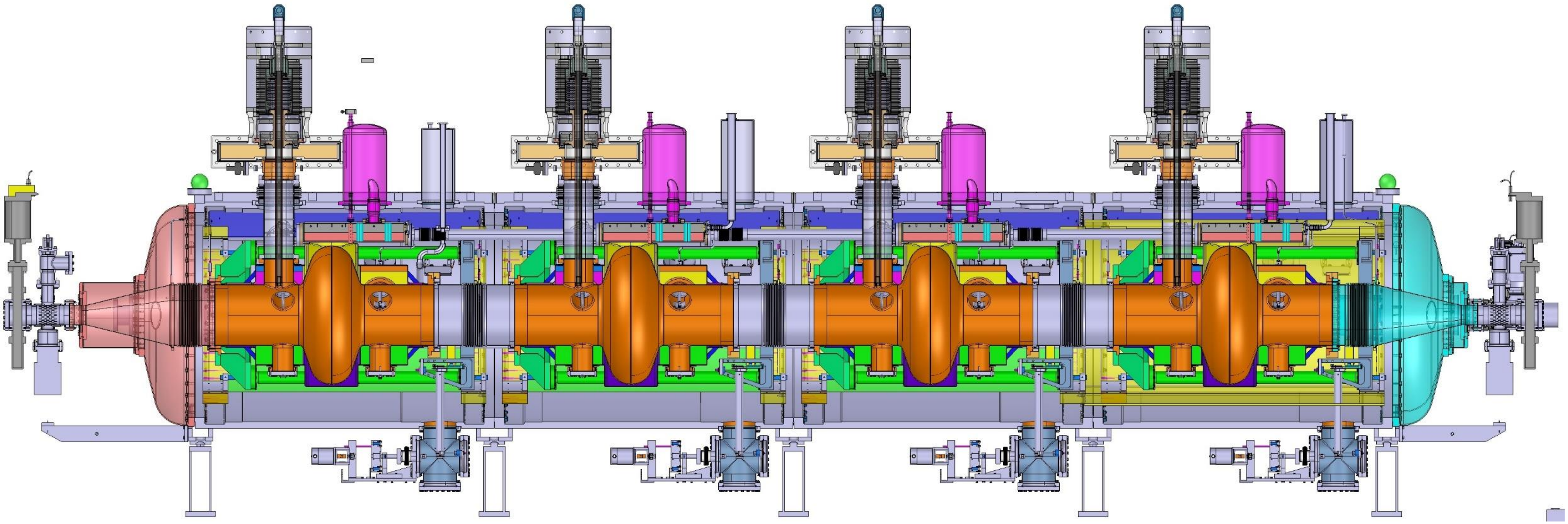
Test results of re-built LHC spare cavities

TTC 2020 – CERN

5th of Feb. 2020

F. Peauger on behalf of the LHC team

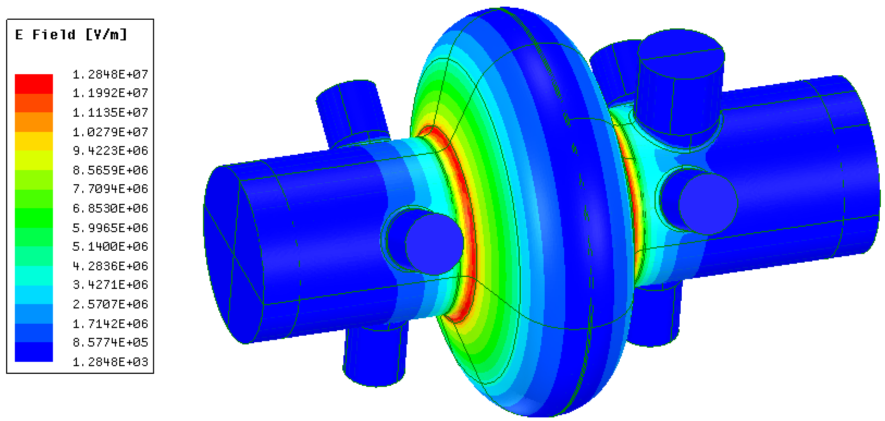


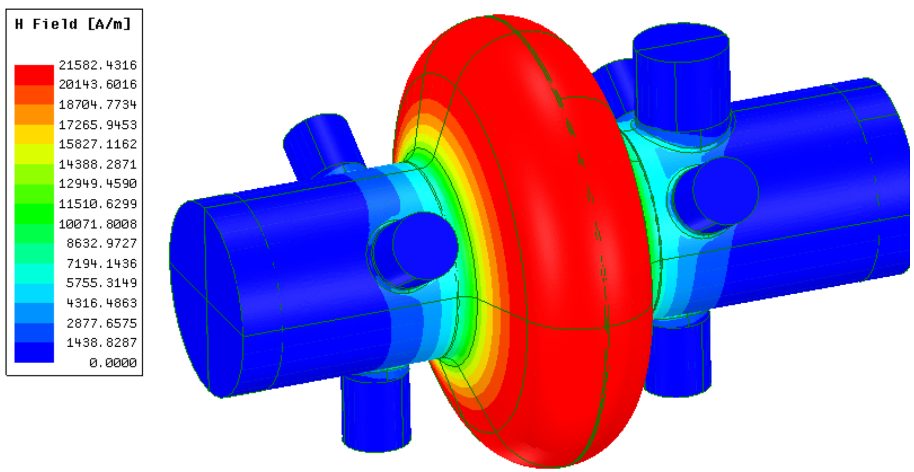
Accelerating cavities in LHC

- Acceleration of high energy ($\beta = 1$) high intensity (0.5 A) proton beams
- 8 RF cavities per beam working at 400 MHz
- 2 beams: 16 cavities in total delivering a total voltage of 8 to 16 MV
- 4 cavities per cryomodule operating at 4.5 K in CW
- Nb thin film on Cu technology
- Fabrication : end of 90's, beginning of 2000's
- In operation since 2008

LHC accelerating cavity RF design parameters

Parameters	Value
Frequency [MHz]	400.79
Operating temperature [K]	4.5
Nominal Accelerating Voltage $V_{acc} = (E_{acc} \times L_{acc})$ [MV]	2
Accelerating length $L_{acc} = (n_{cell}.\beta.\lambda/2)$ [m] with $\beta = 1$	0.374
Accelerating gradient E_{acc} [MV/m]	5.33
Linac r/Q [Ω] at β=1	85.3
Circuit r/Q [Ω] at β=1	42.7
G [Ω]	256.9
Q_0 at operating temperature for R_{BCS}=36.4 nΩ*	7.10^9
Q_0 at nominal gradient	$> 2.10^9$
Cavity dynamic RF heat load [W]	23.4
E_{pk}/E_{acc} at β=1	2.4
B_{pk}/E_{acc} [mT/(MV/m)] at β=1	5.08
Max. surface field E_{pk} [MV/m]	12.85
Max. surface magnetic field B_{pk} [mT]	27.11
Stored energy [J] at nominal E_{acc} and β=1	18.5
Qext	2 to 6.10^4
RF power [kW]	300

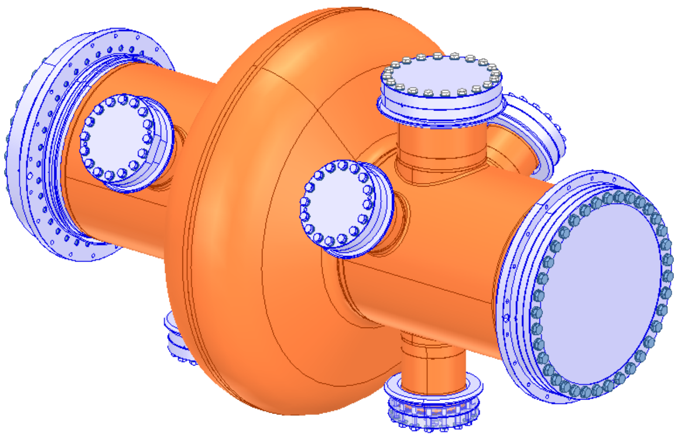


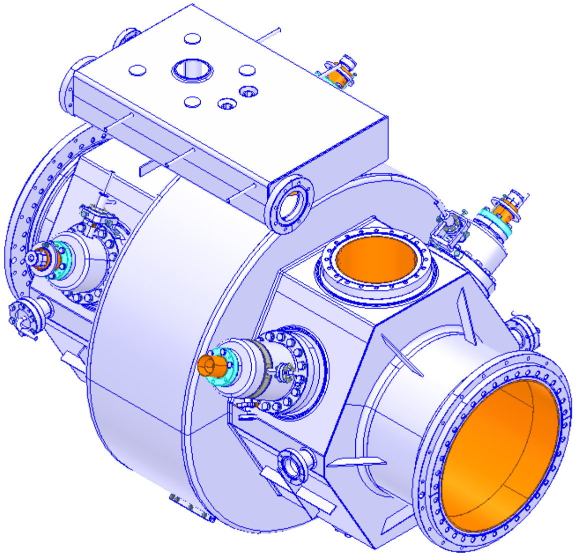


* : Average values from measurements of LHC cavities in the 90's, and post-processed by A. Miyazaki (presented at the CERN SRF2018 workshop)

LHC accelerating cavity technological parameters

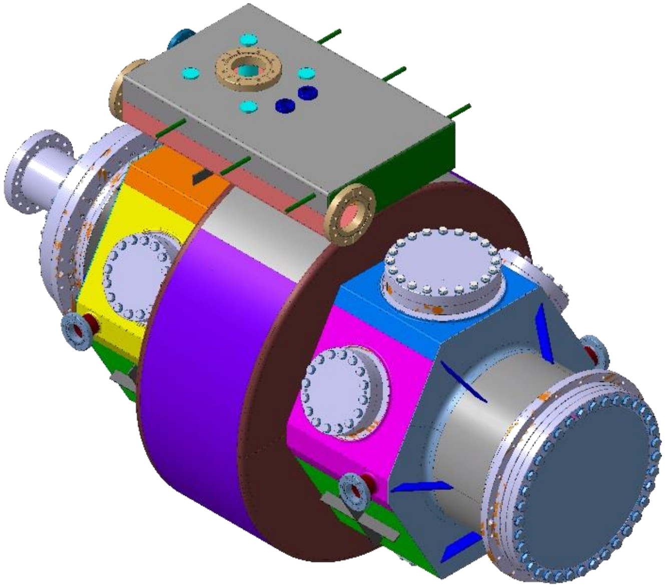
- OFE copper plate shaped by electrohydroforming or spinning
- Electron beam welding and vacuum brazing (flanges)
- Nb-coated on Cu-cavity:
  - 2 x SUBU (100 µm) chemical polishing before Nb-coating
  - 150 °C - 48 h bake-out before coating
  - Magnetron sputtering of Nb
    - sputter gas pressure Kr = 1e-3 mbar
    - cathode voltage = 400 V
    - 1-5 um thickness
- Stainless steel flanges and helium tank (no bellows)
- 1 variable FPC, 4 x HOM couplers, 3 pick-up antenna (2 spares)





Motivation and scope of the project

- Only one spare dressed cavity and one spare cryomodule available
- New project started in 2015 to re-build and qualify <u>four cavities</u> and <u>one quarter cryomodule*</u>



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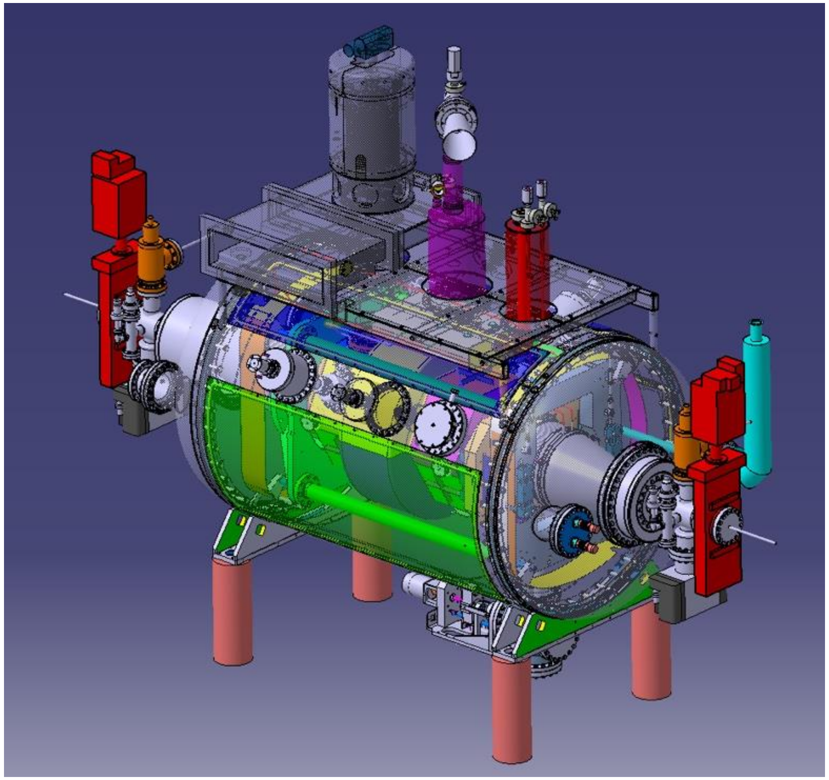
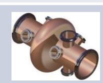
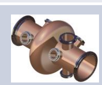


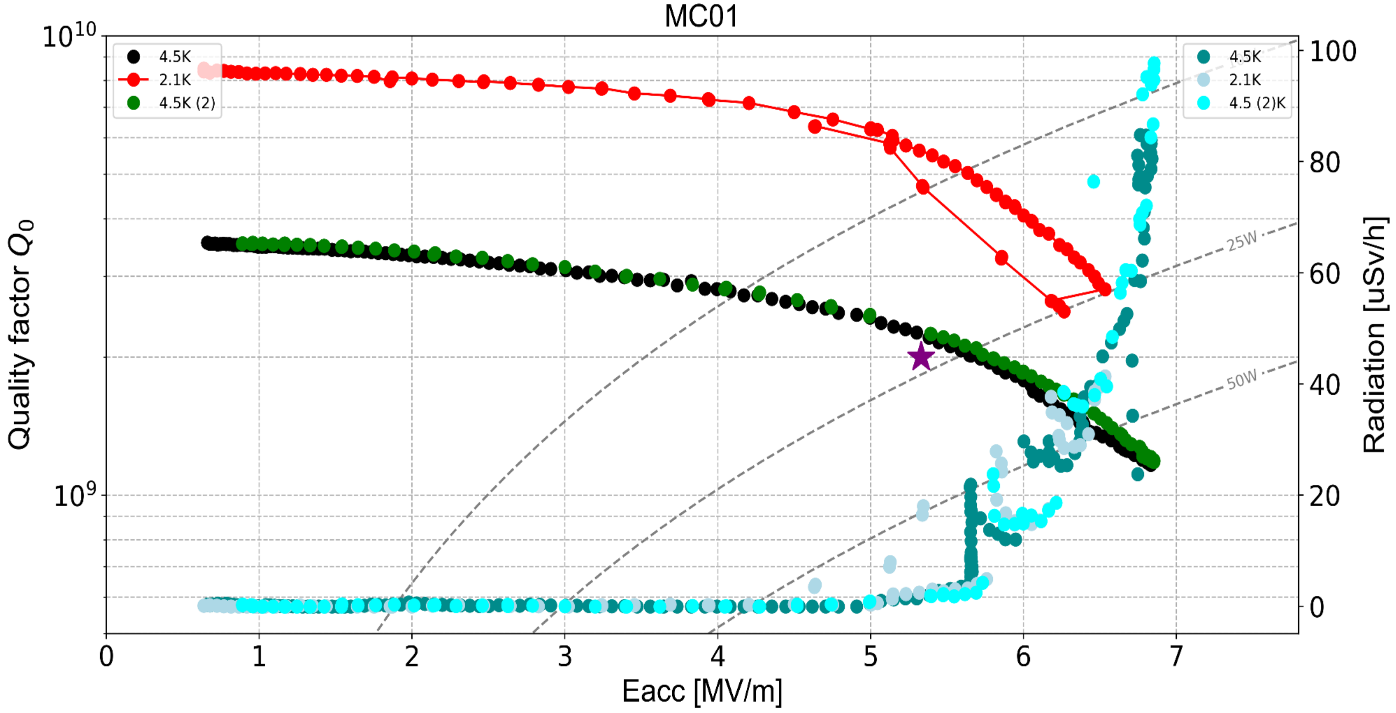
* Original scope was a full cryomodule, but was re-scoped to a 1/4-CM as a first step and training object

Status

ID	Half-cells, Cut-offs, He-tank	Comment	Cold test
PC01.1	2nd gen. Bonitempo (old design), full cut-offs 		Aug-16
PC02.1	2nd gen. Bonitempo (old design), full cut-offs 	Weld projections	Oct-16
PC02.2		Contamination before coating	n/a
PC02.3			Nov-17
LHC19	1st gen. Bonitempo (old design)	Original dressed spare cavity	Dec-17 & Jan 18
PC05.1	Spun and machined RF surface by Heggli (new design), simplified cut-off 	Manually polished welds	Feb-18
PC03.1	1st gen. EHF by BMAX (new design), simplified cut-off, 	Manually polished RF-surface, welds not polished	Apr-18
PC02.3	Dressed cavity, updated He-tank design		Jul-18
PC03.2		Manually polished welds	Nov-18
MC01	Spun and machined RF surface by Heggli (new design), Full cut-off 		Mar-19
NC01	Spun and machined RF surface by Heggli, full cut-off 	HPWR (100 bar) in SM-18 (condensation issues)	Jul-19
PC04	2nd gen. EHF by BMAX, simplified cut-off 	HPWR (50 bar) in SM-18	Aug-19 & Jan-20 on V3
NC02	Spun and machined RF surface by Heggli, full cut-off 	HPWR (100 bar) in SM-18 (hole repaired by welding a Cu-piece)	Nov-19 & TBD with Nb coated flanges
NC01.2		Manual polish of defects, HPWR	TBD

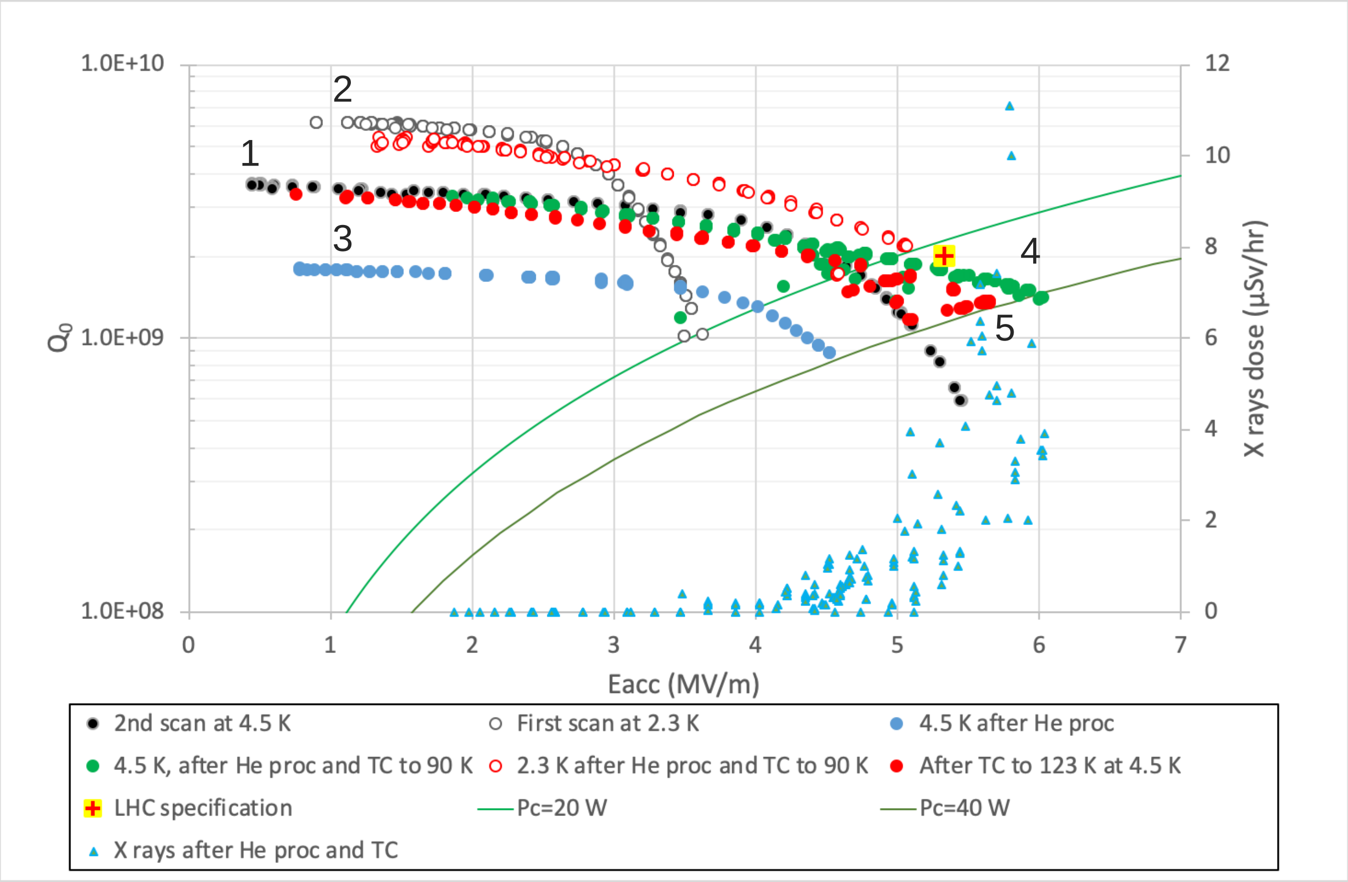
Old cavity cell design systematically 700 kHz off frequency
The cell design was modified (overlength added at the equator)

Bare cavity MC01 test results



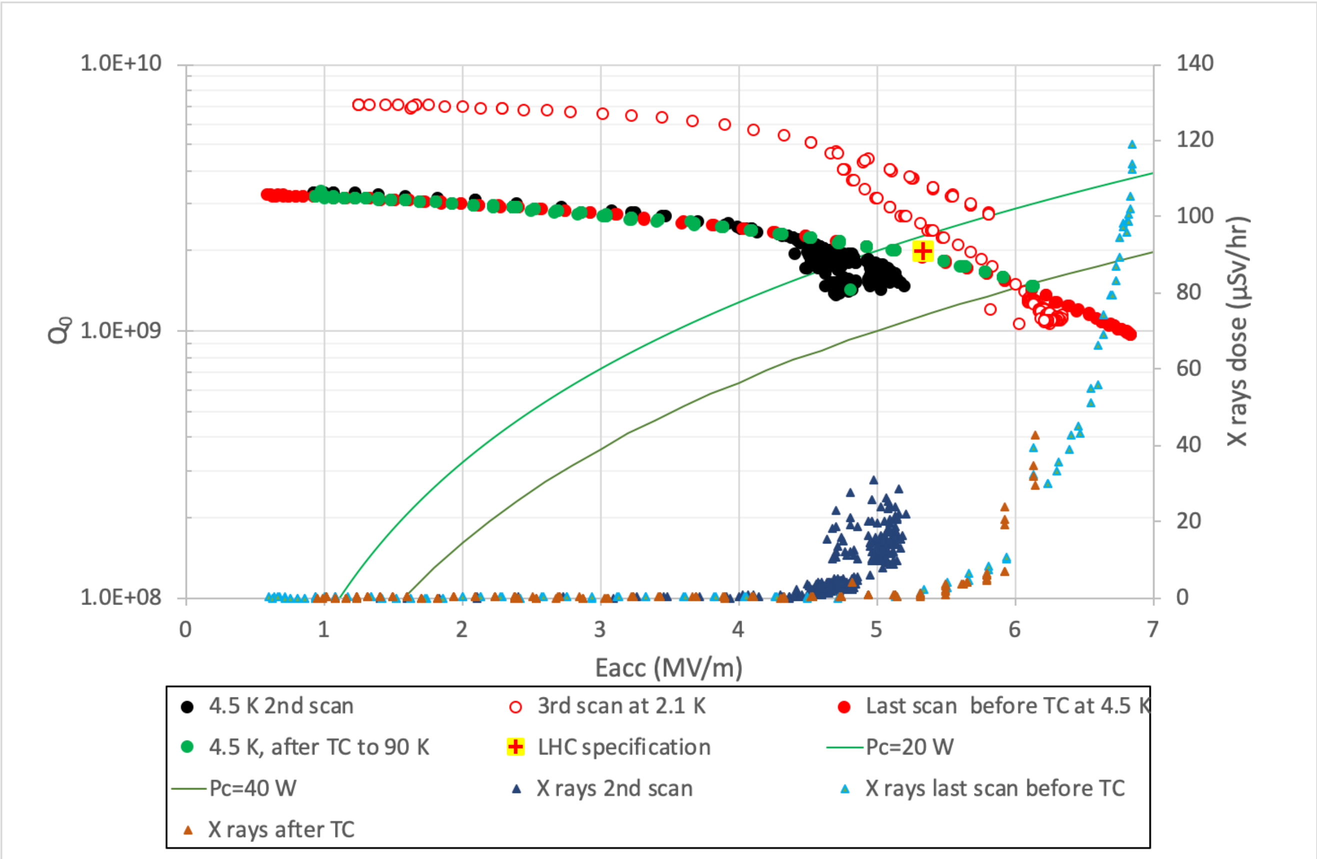
- Initial limitation around 4 MV/m due to FE and Q-drops at 4.5 K
- Meets the spec after RF-conditioning
- Q-drop above 5.2 MV/m at 4.5 K
- Q-drops and hysteresis above 6.5 MV/m at 2.1 K, cause not clear
- **Now integrated in its helium tank and mounted in the 1/4 cryomodule**

Bare cavity NC01 test results



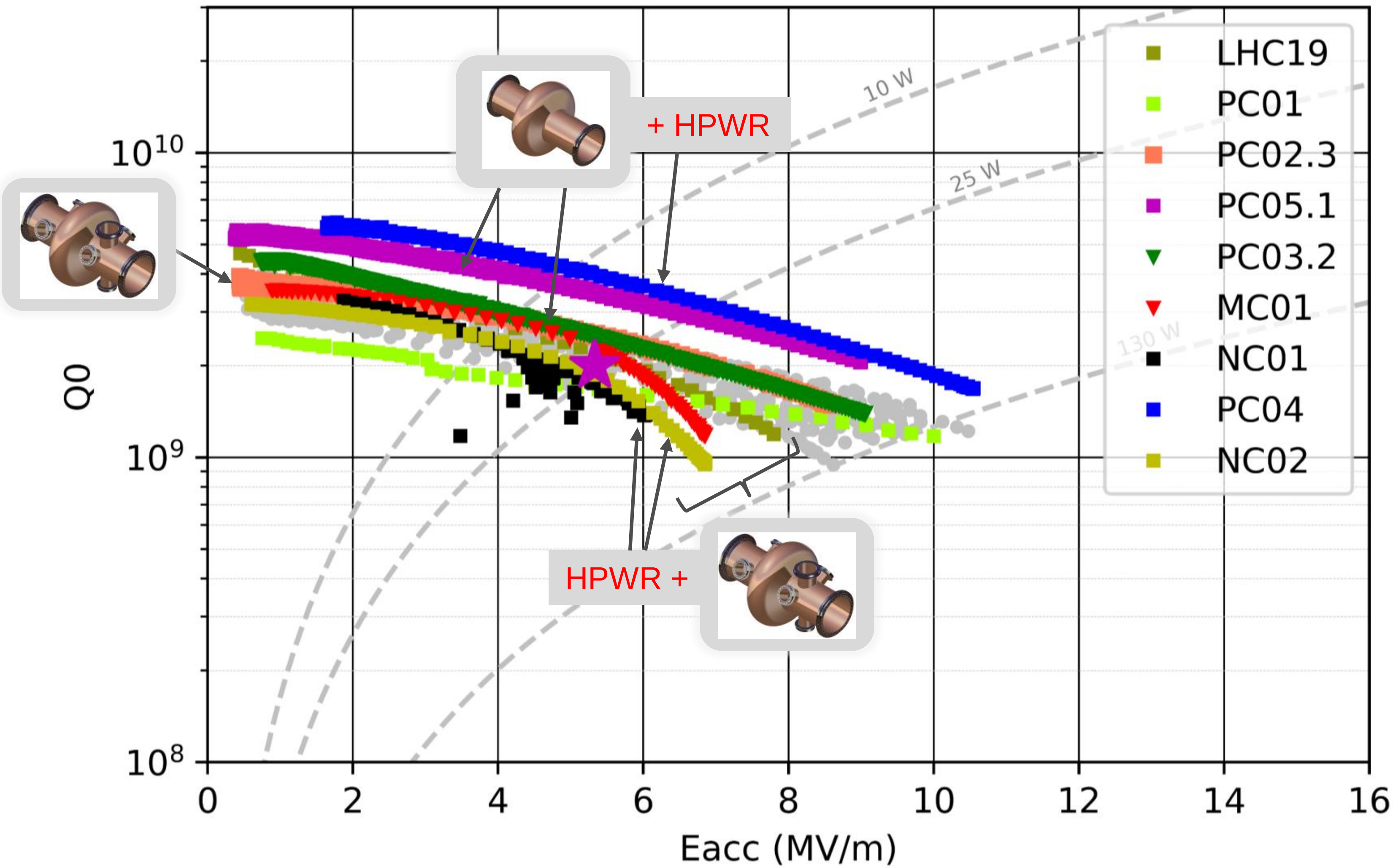
- FE at 3-4.5 MV/m after He- and RF-processing and 2 thermal cycles to 90 K and 123 K
- Performance limited by FE and did not meet the spec
- **Re-coated after stripping, manual polishing of surface defects + SUBU => NC01.2**
- **Cold test of NC01.2 early 2020**

Bare cavity NC02 test results



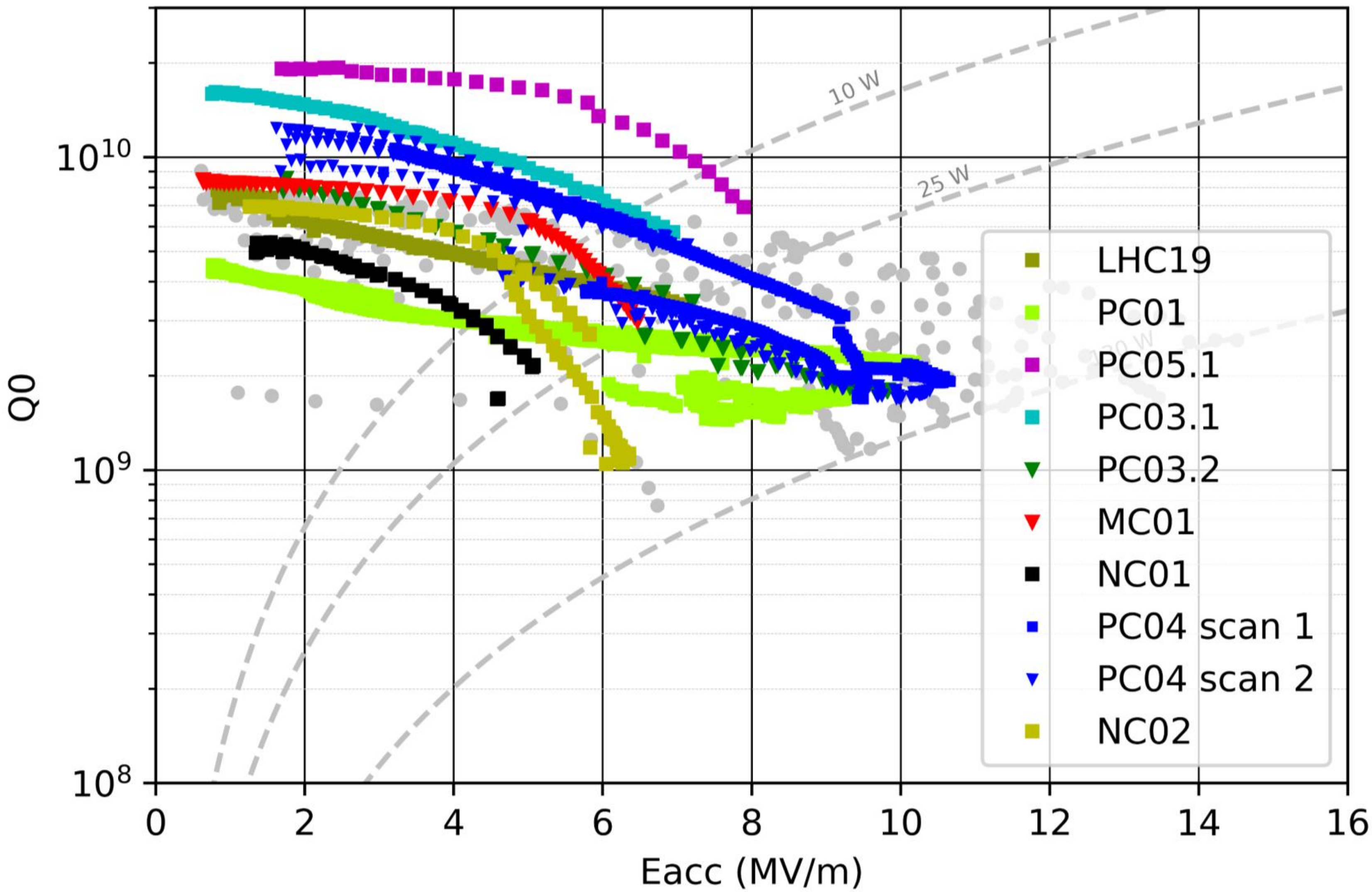
- FE initially 4-4.5 MV/m, quickly suppressed by RF-conditioning
- Performance similar to NC01.1 and slightly below the spec (1.96E+09)
- Assemble with PC03 antenna flanges and Nb-coated DN100/150 to test “full vs simplified”
- Eventually, strip, manual polish of surface defects + SUBU => NC02.2 (TBC)

All test results at 4.5 K



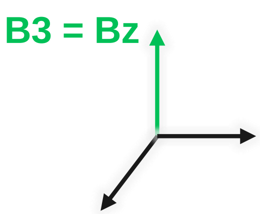
In average, we notice a decrease by a factor of 2 in Q0 between simplified cavity and cavity with ports.
This could be achieved by increasing the surface resistance on the Nb film inside the ports cylinders (4 HOM ports, 2 pickup ports and 1 FPC port) from **40 nΩ** to **90 µΩ** ! Can a tilted growth induce such high Rs?

All test results at 2 K



Re-test of PC04 cavity

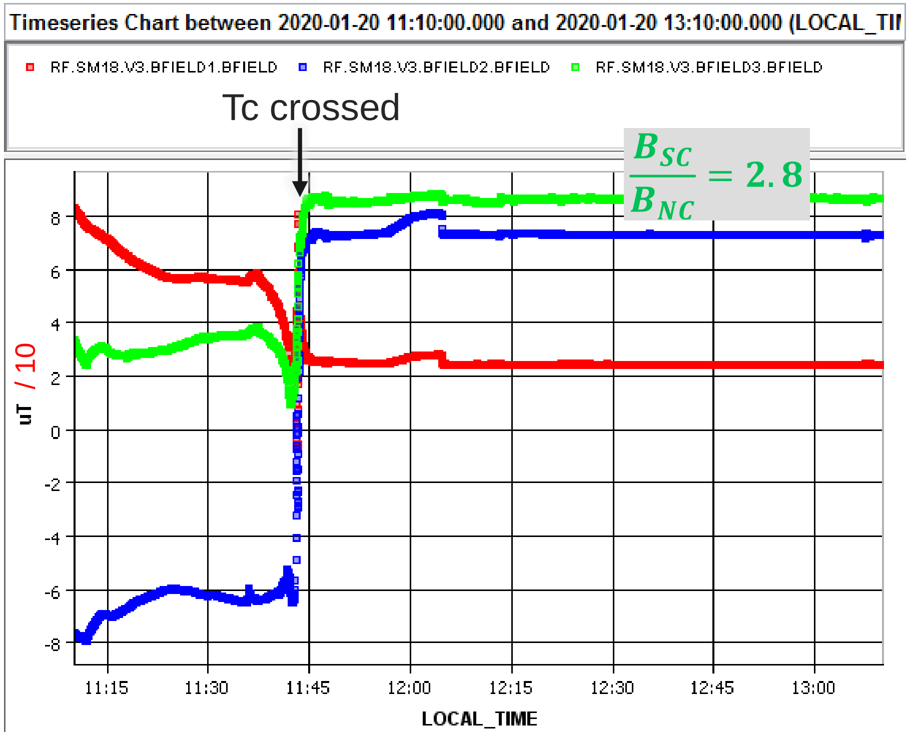
- Main idea: re-test PC04 cavity in different environmental conditions:
  - V3 cryostat (instead of V6 cryostat usually used for LHC cavities)
  - Better operation at 2 K and below
  - Possibility to compensate earth magnetic field
  - Digital SEL RF system
  - Advanced instrumentation



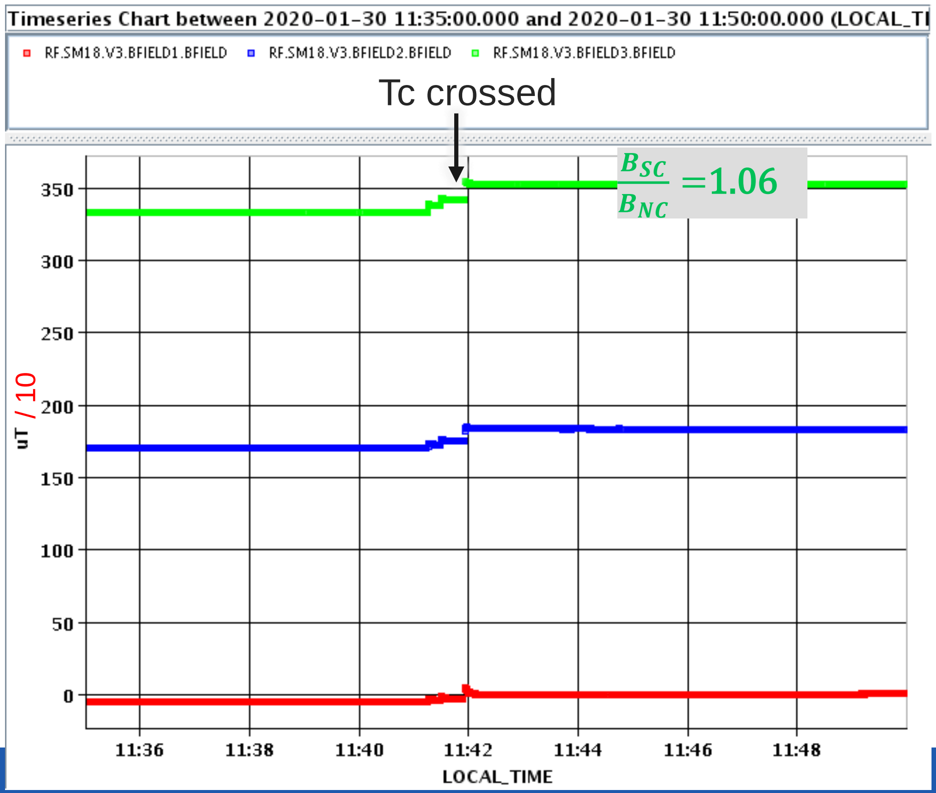
Flux expulsion

- Two sets of ambiant B field values were tested with the following sequence:
  - Cooldown from RT to 4.5 K, with Bz = 0.3 – 0.8 uT and cooldown speed of -0.9 K/min
  - RF measurement
  - Warm-up to 15 K
  - Cooldown from 15 K to 4.5 K with Bz = 33-35 uT and cooldown speed of -0.4 K/min
  - RF measurement

Bz = 0.3 – 0.8 uT

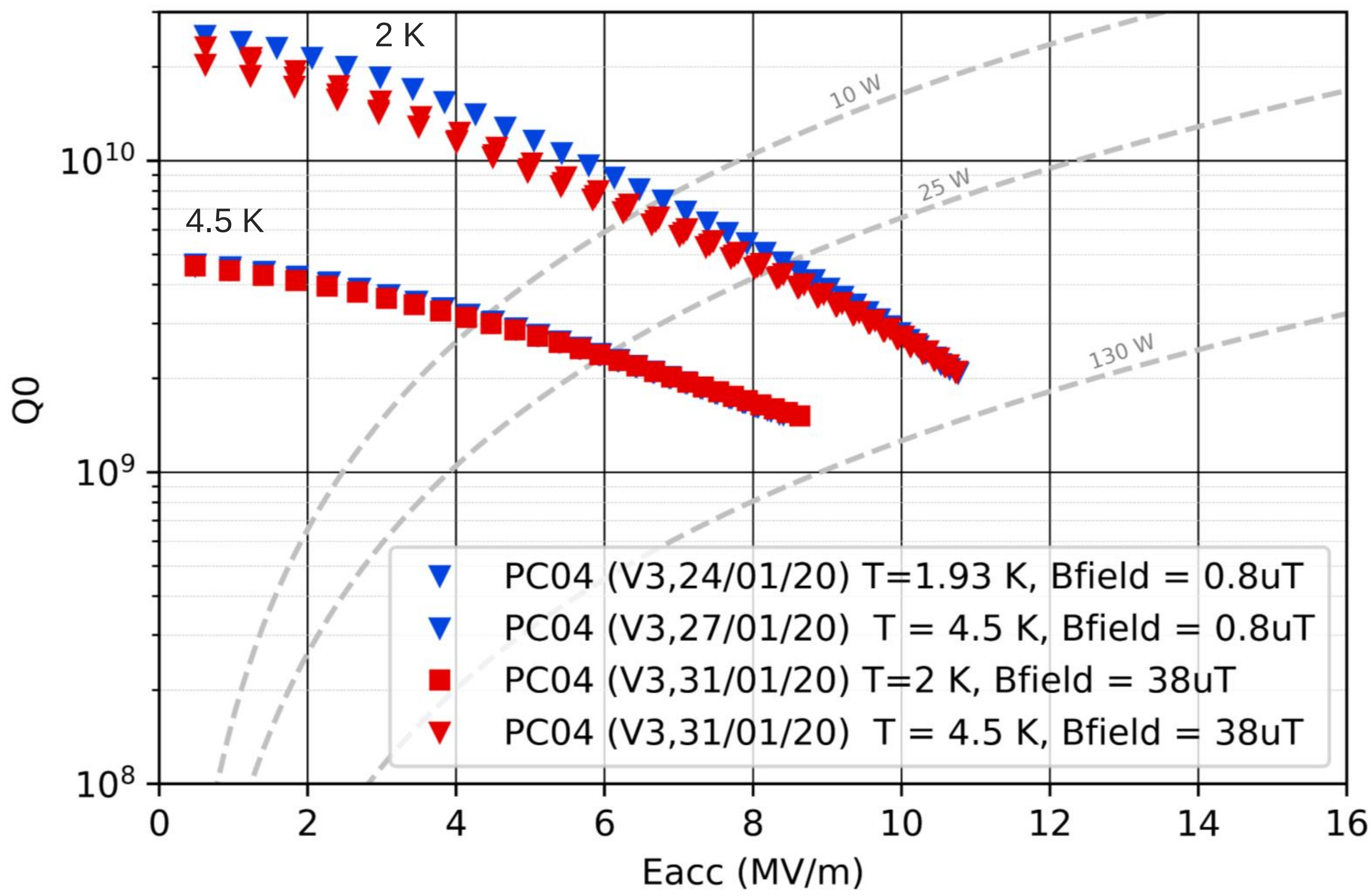


Bz = 33-35 uT

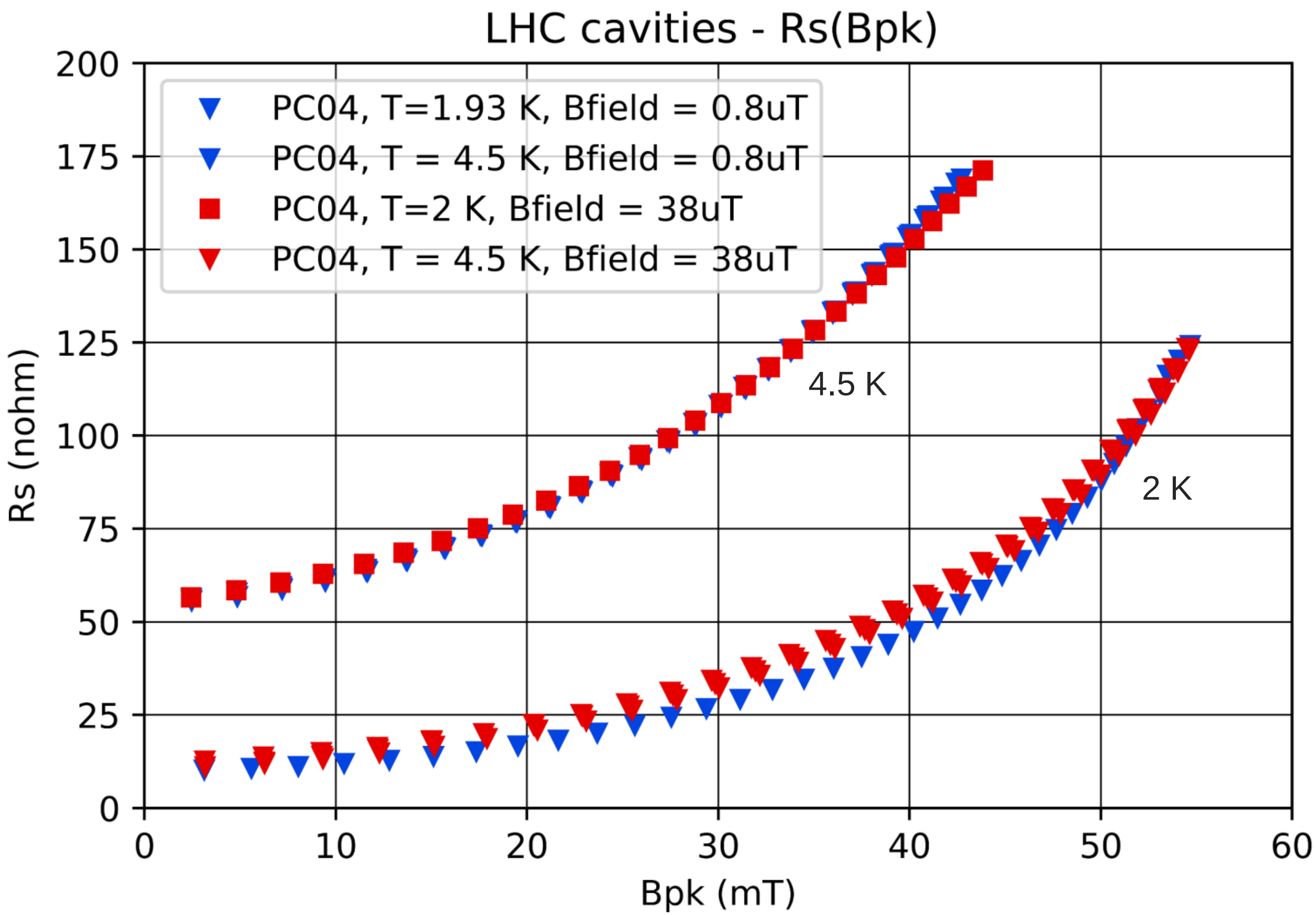


Remark: magnetic field uniformity of V3 to be checked

Q(Eacc) sensitivity to ambient B field

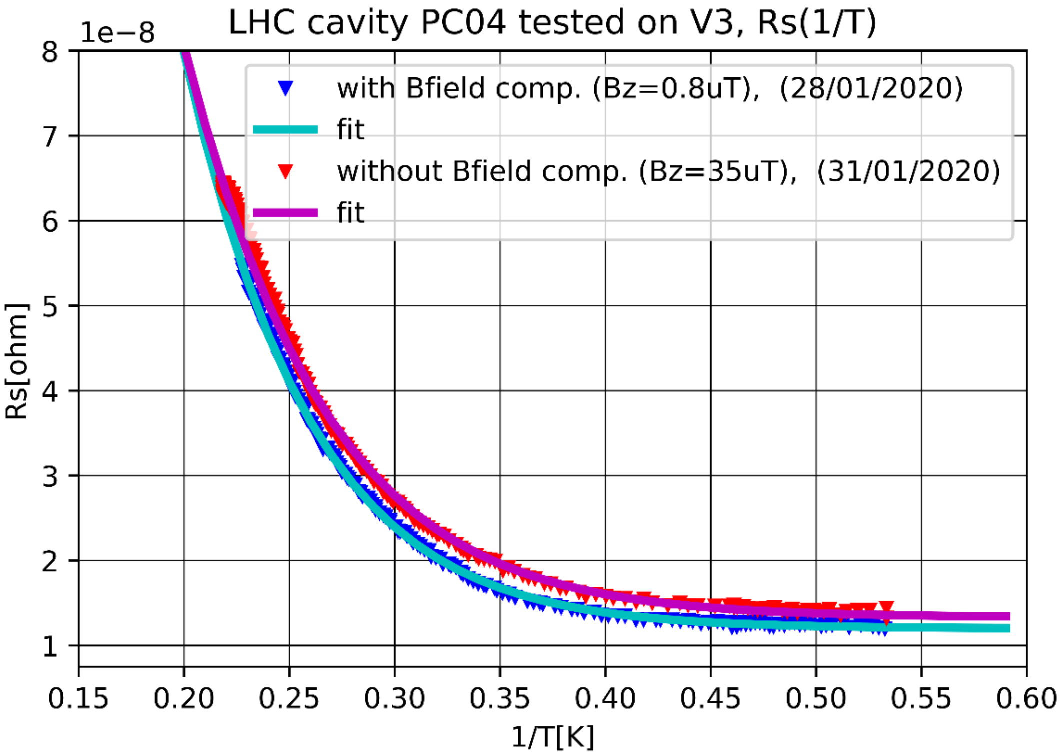


Rs(Bpk) sensitivity to ambient B field



Rs(1/T) sensitivity to B field

- **Measured at 1 MV/m**
- **Fit with BCS theory**



$$R_s(T) = A(\lambda, \xi, l, v_F)\frac{\omega^2}{T}\exp\left(-\frac{\Delta(0)}{k_B T}\right) + R_{res}$$

Parameters	With B field compensation	Without Bfield compensation
A [nΩK]	3900.8	2638.0 (-32%)
$\Delta = \Delta(0)/k_B$ [K]	21.43	19.52 (-9%)
R_{res} [nΩ]	12.01	13.32 (+10%)

- **Sensitivity for Rres: 3.8 nohm/gauss**
- **The A factor is quite sensitive to flux trapping**

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Conclusion

- 8 cavities have been fabricated and tested in vertical cryostat over the last 5 years (14 tests in total, (4 tests in 2019))
- 3 cavities have been re-coated, and some cavities needed to be manually polished (welds)
- Good performances achieved for simplified cavities, but less obvious for cavities with RF ports
- HPWR introduced recently
- Different Q0 behavior (Q0 at low field, Q slopes) between simplified cavities and cavities with RF ports still not understood
- Confirmation that V6 test stand is limited at 2 K
- Magnetic flux trapping : low sensitivity on residual resistance experimentally confirmed

Acknowledgments

BE-RF:
S. Bizzaglia, J. Biessy, O. Brunner, Y. Cuvet, M. Gourragne, M. Karppinen, A. Macpherson, P. Maesen, A. Miyazaki, F. Peauger, G. Pechaud, E. Sancho Cabrera, K. Schirm, N. Schwerg, D. Smekens, N. Stapley, M. Therasse, K. Turaj, N. Valverde, W. Venturini, A. Xydou

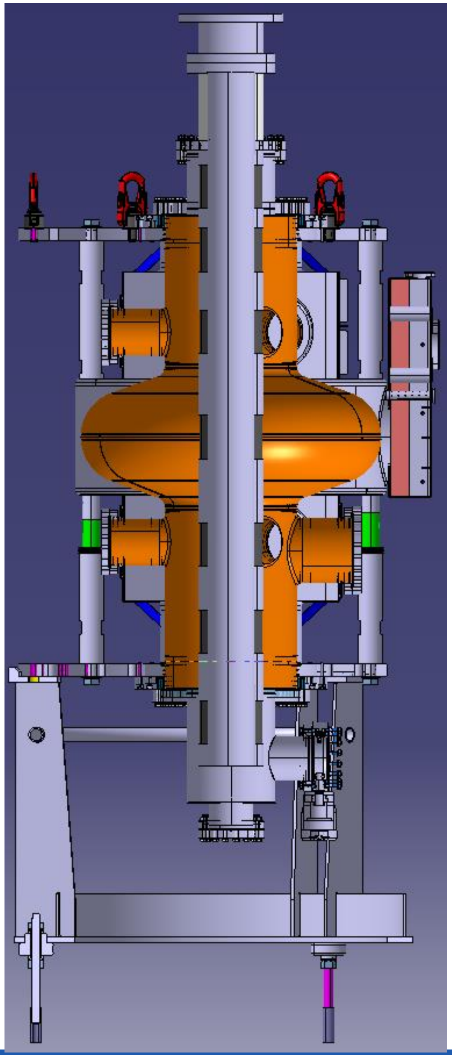
EN-MME:
C. Abajo Clemente, S. Atieh, E. Cantergiani, O. Capatina, A. Cherif, R. Claret, L. Dassa, G. Favre, JM. Geisser, T. Mikkola, L. Mettler, F. Motschmann, P. Naisson, F. Pillon, T. Tardy, P. Trubacova

TE-VSC:
S. Calatroni, L. Ferreira, S. Forel, P. Maurin, G. Rosaz, M. Taborelli, M. Thiebert, L. Viezzi

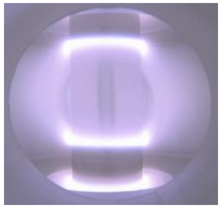
HSE:
C. Arregui

Courtesy of G. Rosaz TE-VSC

DC Magnetron sputtering



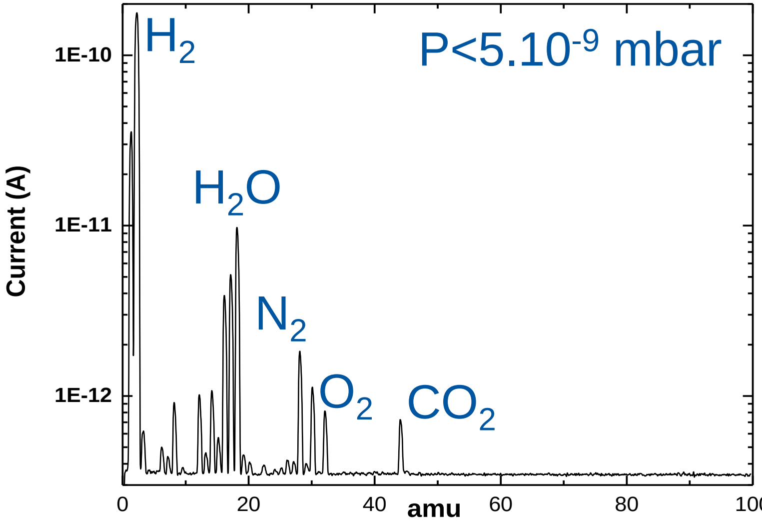
Courtesy of G. Rosaz TE-VSC

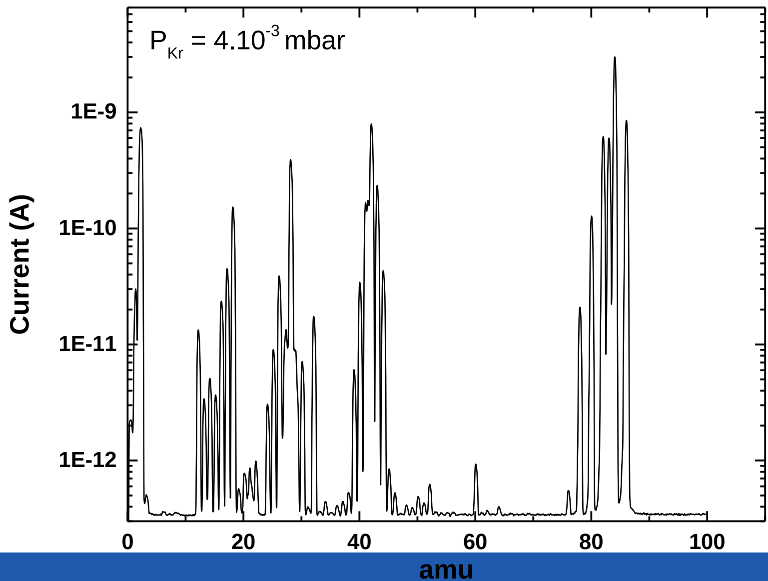


Coating Parameters

- Bakeout: 150C for 48h
- Typical gas composition before coating:
  - High quality vacuum
  - $H_2O << H_2$
  - No amu > 50
- Coating procedure
  - Upper cut-off / Lower cut-off (3 positions)
    - $P_{Kr} = 4.10^{-3}$ mbar
    - 400V / 7A
    - Average temperature ~ 70C
    - ~ 40 min per cut-off
  - Cell
    - $P_{Kr} = 1.10^{-3}$ mbar
    - 400V / 15A
    - T_{max} = 150C
    - 65 min

Identical parameters for PC01.1 and PC02.1





- Calatroni:
- http://inspirehep.net/record/788517/files/jpcs_114_1_012006.pdf
- “As an order of magnitude the effect is 100 nΩ/Gauss of external magnetic field for bulk Nb, and only 1 nΩ/Gauss for films. “