US cold RF test program of DQW prototype cavities

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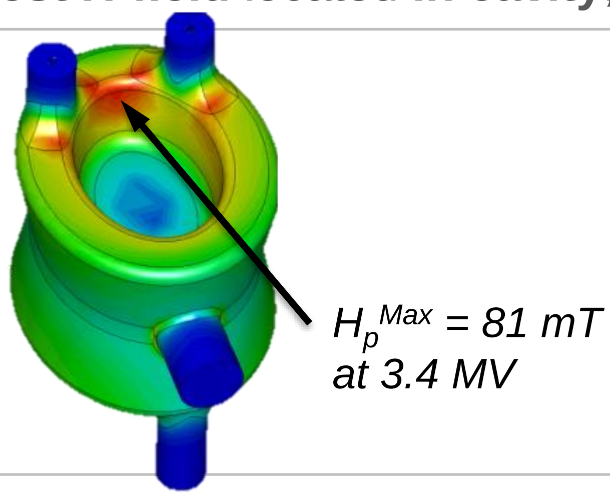
https://indico.cern.ch/event/742082/

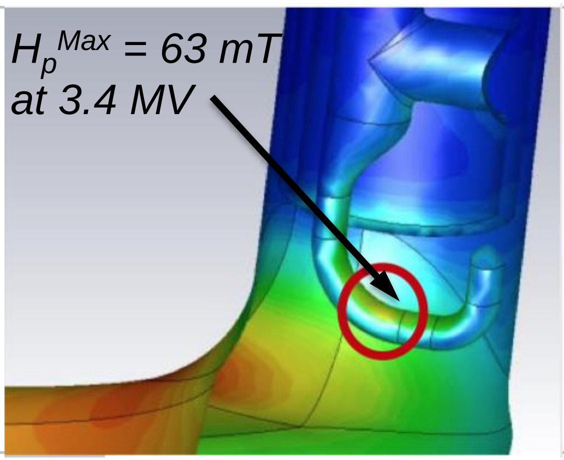
Refresher

- In 2013, cold RF tests of a **PoP DQW cavity demonstrated** the possibility of delivering **required crab kick** (3.4 MV) reaching 4.7 MV while **meeting spatial constraints** from LHC.

- Design **reviewed to meet spatial, RF requirements** (HOM damping, heat load, etc.) for **testing in SPS and operation in LHC: DQW SPS-series**.
  - Features **11% lower peak H-field**.
  - **Highest H-field** located **in cavity**, not in filter.



DQW SPS cavity



and its HOM filter

H-field distribution for fundamental mode (400 MHz) of DQW SPS

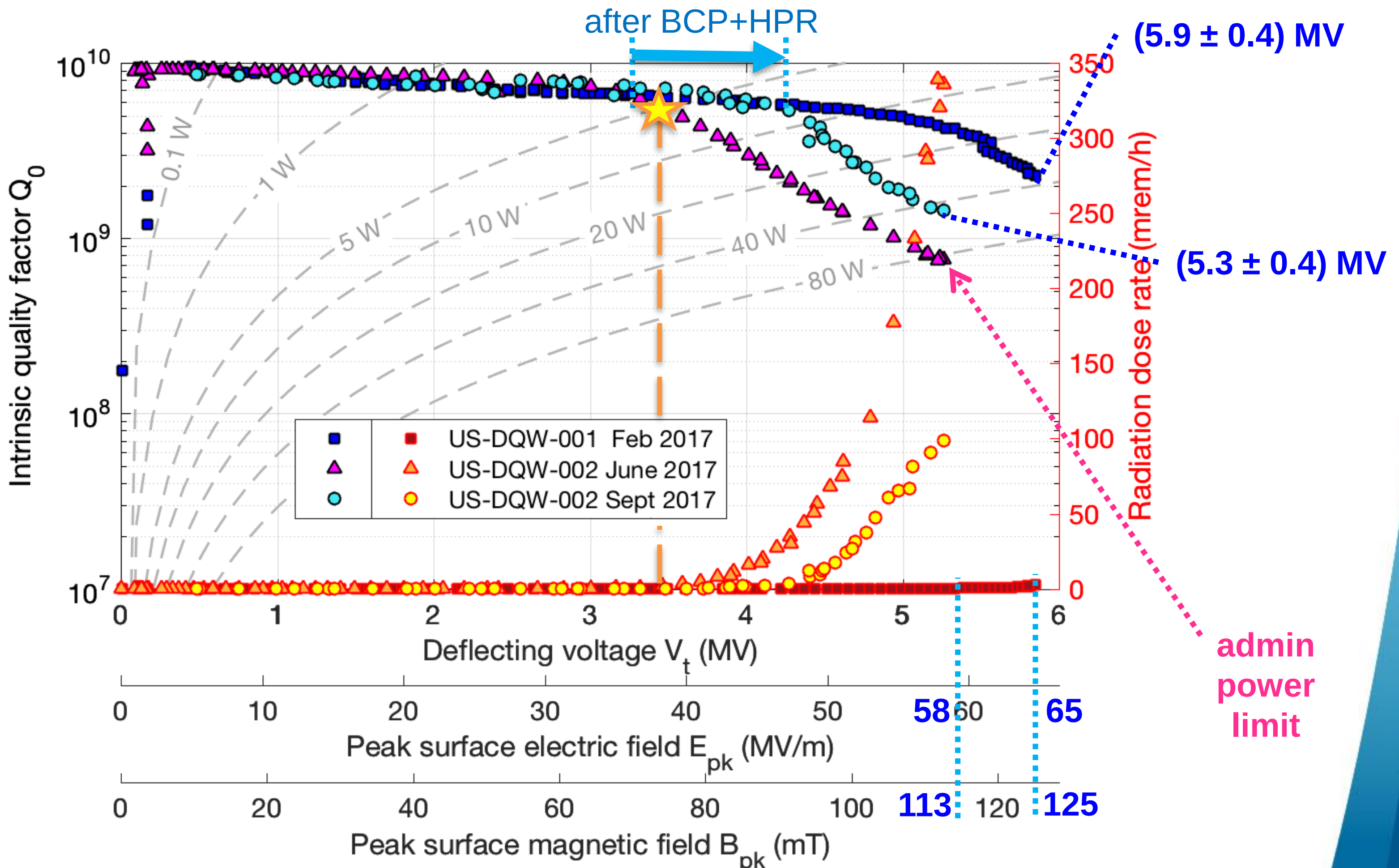
Refresher

- **Four** (4) identical **DQW SPS-series** cavities **fabricated:**
  - Two prototypes built in the US (Niowave Inc. and JLab).
  - Two cavities built at CERN, fully dressed into cryomodule, being tested in SPS.

- The DQW **prototypes proved useful** learning tools **to:**
  1) assist **fabrication, tuning** and
  2) in **FY2018**, **investigate limited 2K RF performances** of **DQW+filters**
     - CERN DQW SPS-series cavities with three (3) HOM filters quench at 3.4 MV

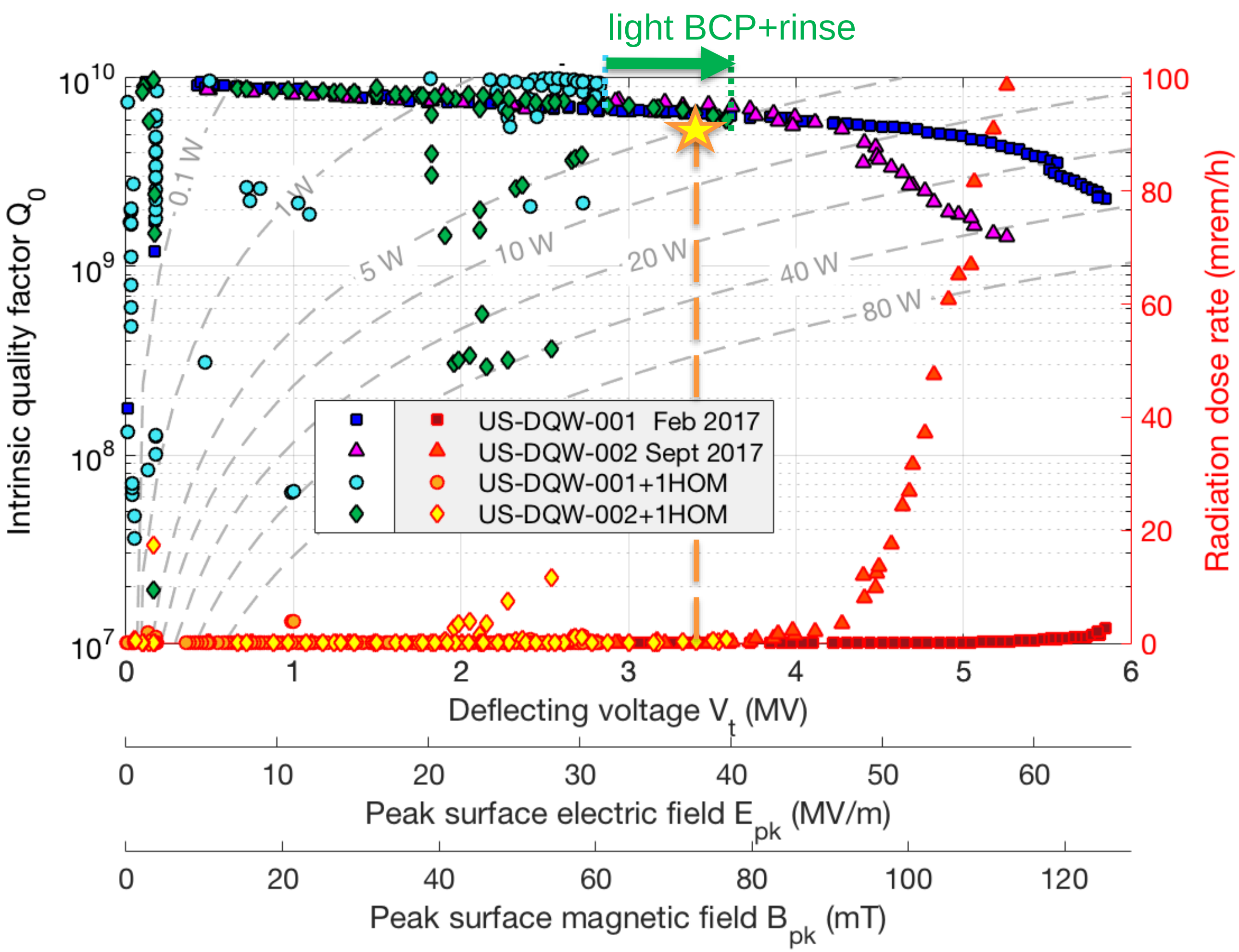
FY2017: cold RF performance of bare DQWs

- **Exceeded** nominal deflecting **voltage** (3.4 MV) with 40% margin; **heat load < 5 W as required**
- **Excellent** performance of **bare cavities** beyond nominal (up to 5.9 MV).
  - Large peak fields reached (~ 30 MV/m TESLA-type cavity)
  - FE onset at Vt = 4.1 MV (above nominal deflecting voltage)
  - Pretty low surface resistance (9 nOhm)



FY2017: cold RF perf. of bare DQW + HOM filter

- The **same HOM filter** tested with cavity #1 and cavity #2.
- **Light BCP** in HOM filter **between tests**: increased quench field **from 2.8 to 3.6 MV**.
- Quench for the two cavity+HOM tests at significantly **lower voltage than for bare cavity** tests.
- Sharp quench, but **no significant radiation** increase, **nor multipacting** (closest band at 2-3MV).



FY2018: high performance program

FOCUS

- Inspect **ultimate RF performance** of **bare DQW cavity + HOM** filters

Goal: 3.4 MV (**NOMINAL**) + 20% margin = 4.1 MV

HYPOTHESIS

- **HOM filter limiting RF performance** due to **insufficient surface treatment**.

[For previous tests HOM filter received 20 um BCP + manual pressure rinsing; compare to standard 150 um BCP + 600C bake + 20 um BCP + HPR + 120C bake for SRF cavities.]

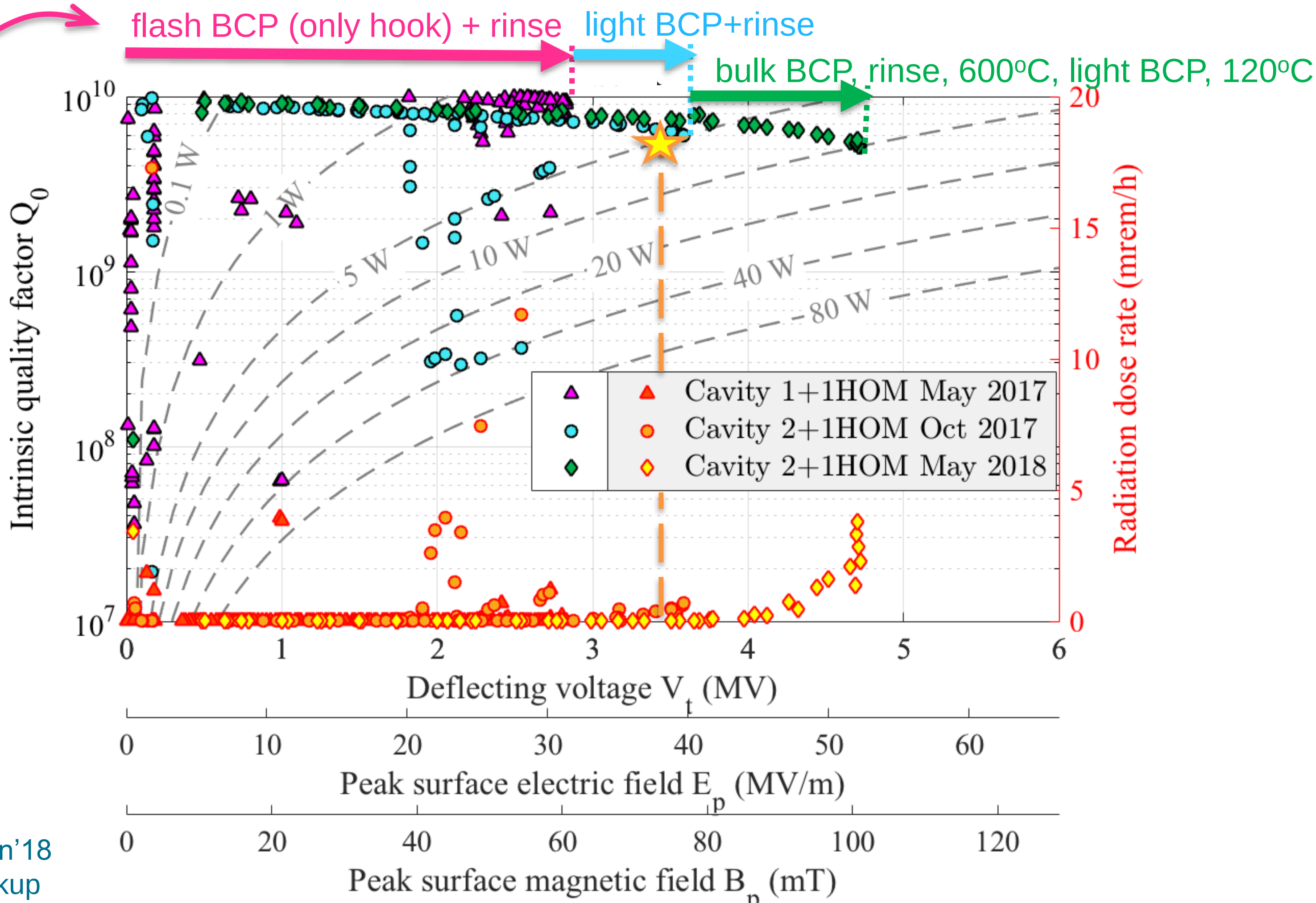
TESTS

1) **Effect of surface treatment** on cavity + HOM filter performance
2) Retract HOM filter to **discriminate if quench** is coming **from cavity or from filter**

FY2018: high performance program

EFFECT OF SURFACE TREATMENT

- Cavity + HOM filter **reached 4.7 MV** (largest Vt to date in any DQW+HOM).
- **No evidence** of **High-Field Q-Slope (HFQS).**
- *Lesson learned:* **HOM filters** should receive **same surface treatment as** any other **SRF cavity**.



Oct’17 run II and Jan’18 not shown: see backup

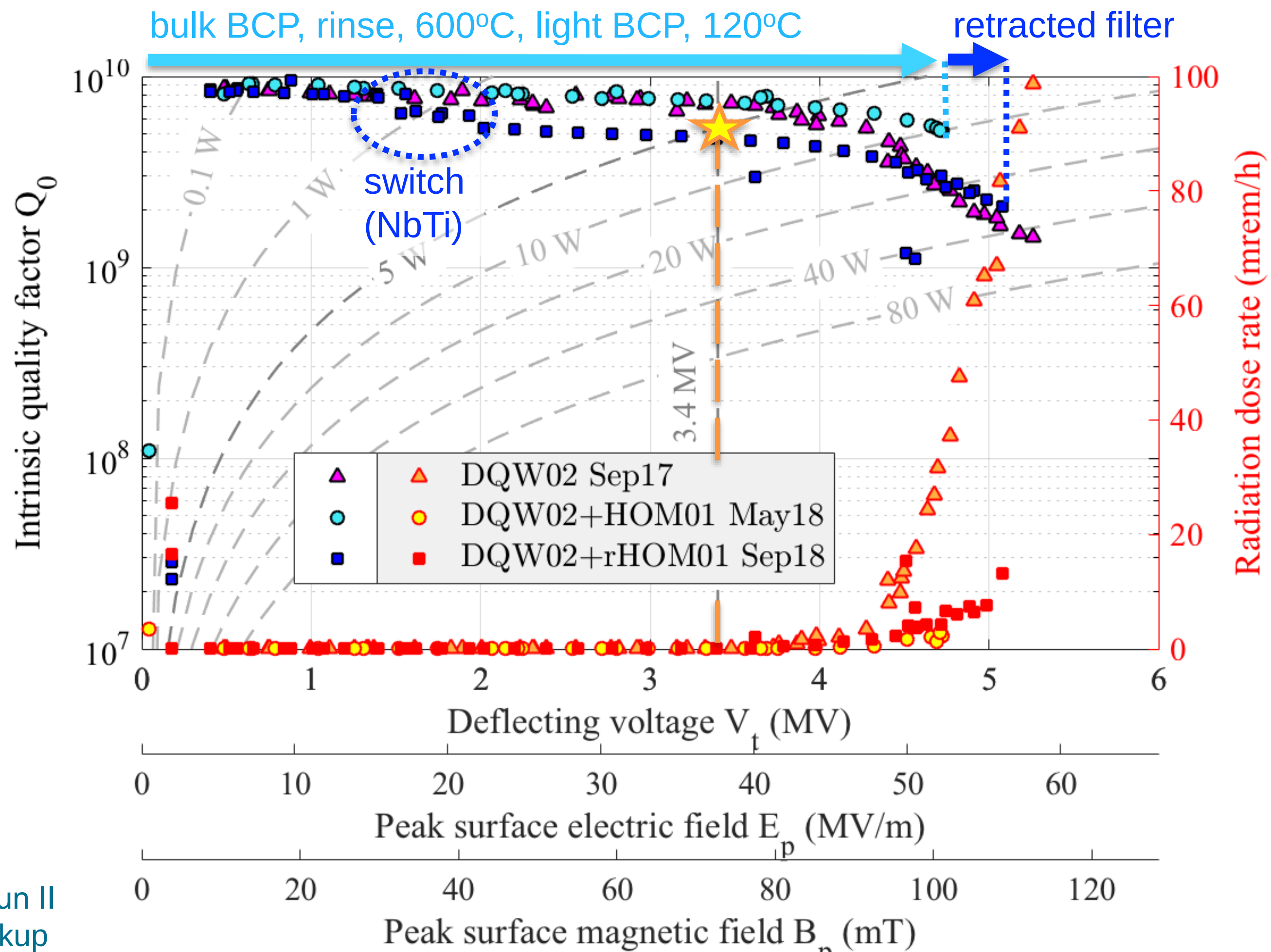
FY2018: high performance program

EFFECT OF HOM FILTER

- **Retracted filter** using 20 mm spacer **reduces Bp in hook by 50%,** allows reaching **Vt ~ 5.1 MV.**

  Assume May18 test was limited by Bp(filter) ~ 120 mT. With spacer, the field in hook is only 60 mT, so the field in the cavity will be now the limiting factor. That is, we will expect voltages around 5.3 MV.

- **Q-switch** due to **NbTi spacer becoming normal conductor**: Q-switch ~ 1.7e10 ⇔ σ = 1.3e6 S/m.



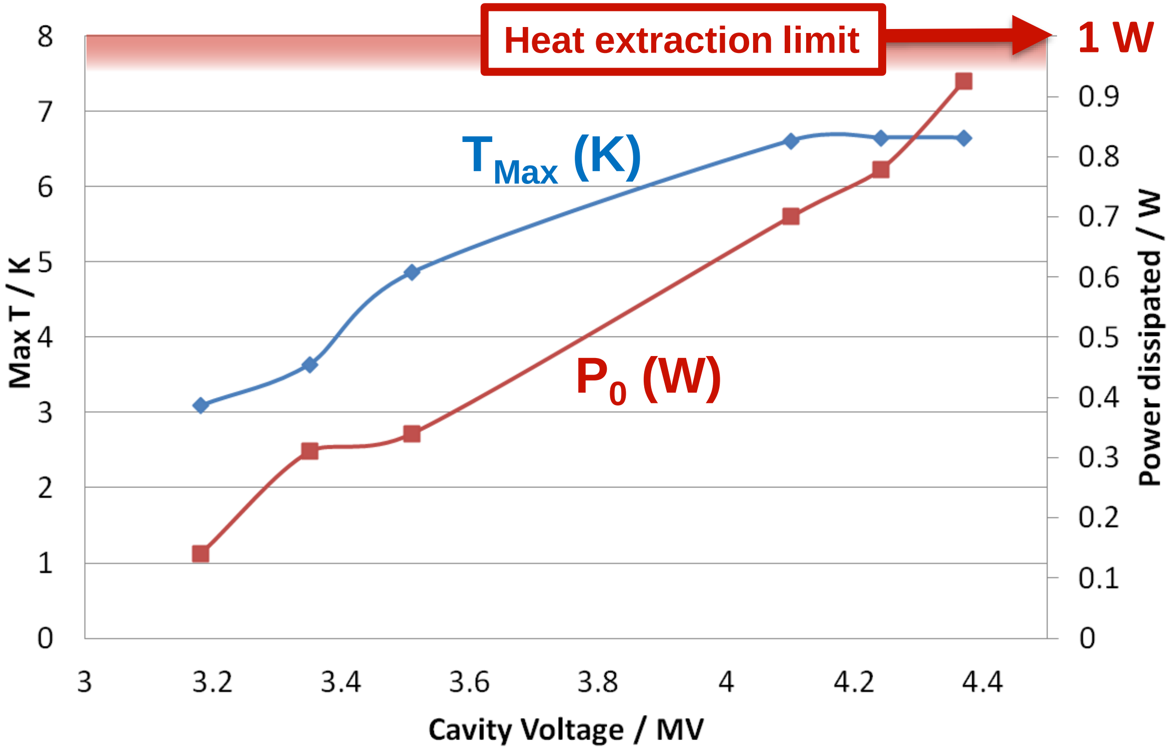
Jul'18 and Sep'18 run II not shown: see backup

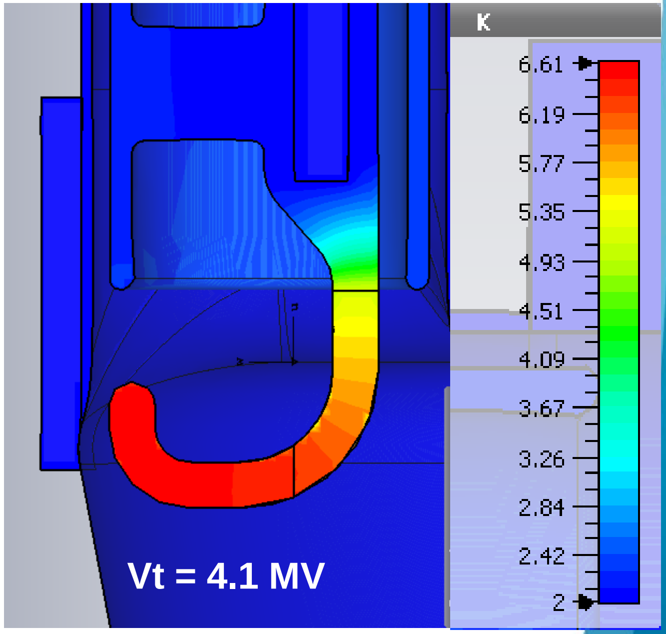
FY2018: high performance program

Why would the HOM filter limit the cavity performance?

- The **cooling channel** of the HOM filter is **sized to extract 1 W** heat max.
- **For Vt > 4.5 MV**, power **dissipated** in the hook is **larger than 1 W** and filter becomes **thermally unstable**, what probably causes the **quench at 4.8 MV**.
- **Retracting** the HOM filter would **reduce the dissipated heat** in the hook.

From CST simulations using R_{res} = 5 nOhm, K = f(T) [G. Burt]

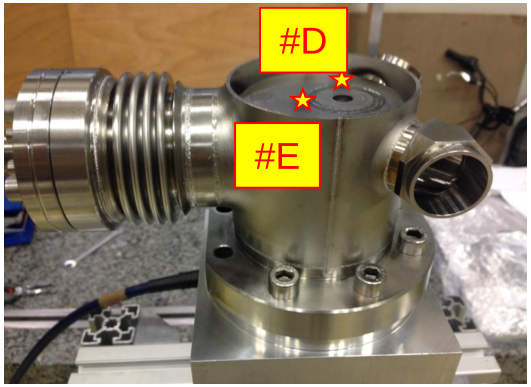




Quench location for bare DQW + HOM filter

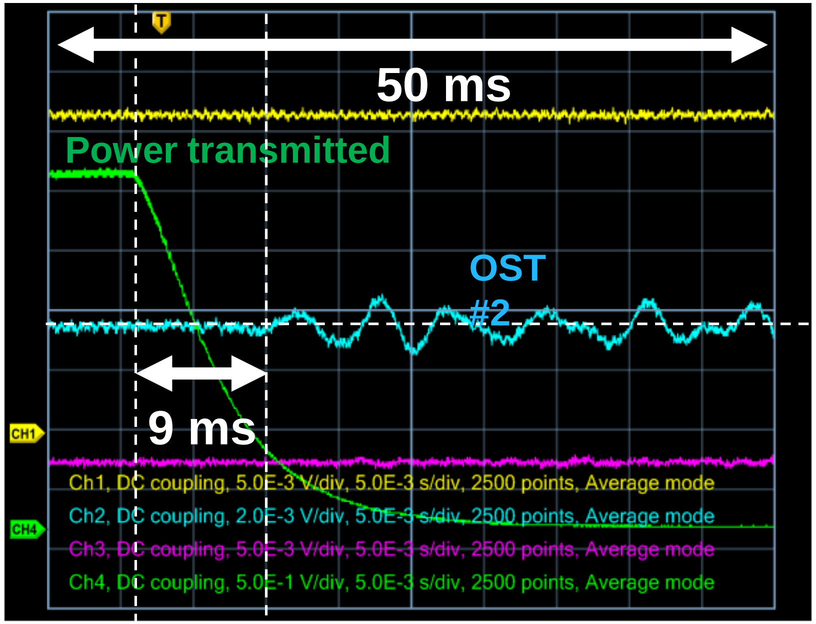
THERMOMETRY (CERNOX)

- Temperature increase on filter registered for several tests (May’17, Oct’17, Sep’18).

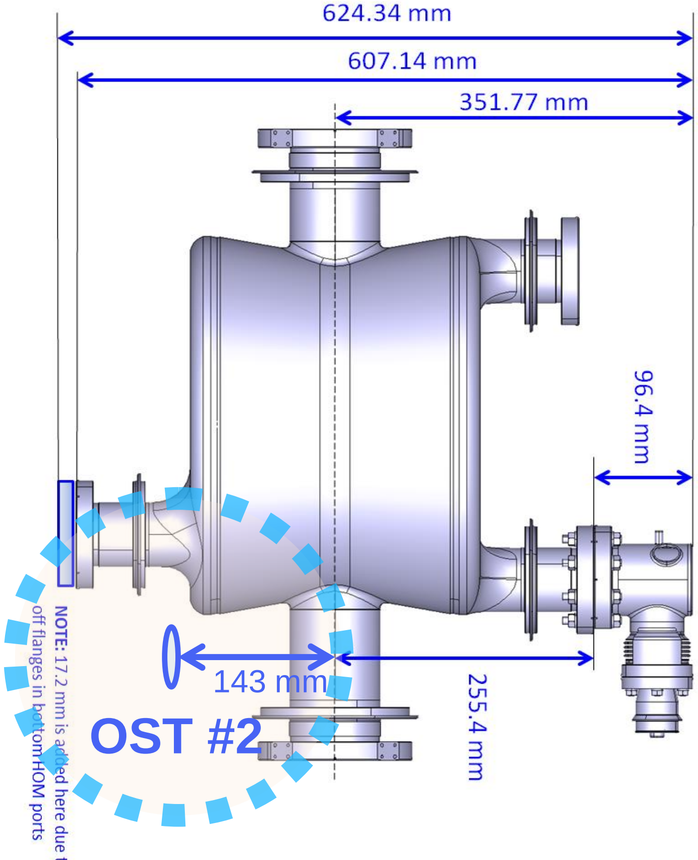


SECOND SOUND DETECTION (OSTs) *(only used in May’18 test)*

- Non-conclusive: The 0.14-m-radius sphere envelope **lies on high H-field region, far from filter**. **No signal from the other OST** looking at same point but far from region.



OST signals and transmitted RF power before, during and after quench.



Multipacting bands

- The **multipacting predictions** by ACE3P and CST **matched well** the multipacting bands **found during the tests**.
- A **recurrent multipacting band,** below 0.5 MV, related to multipacting in the cavity waist as predicted by ACE3P and CST, is **found in every single test**.
- **Other** multipacting **bands processed** and never came back in following tests.

Predicted [Z. Li, G. Burt]			*Found during tests with or w/o filter*	
MP band [MV]	Region	Code	MP voltage [MV]	Comments
(0.26)	Cavity waist	CST	0.17, 0.2	Hard.
(0.1 – 0.5)	Cavity waist	ACE3P		
(2.12)	HOM stub	CST	(1.8 - 2.3)	Soft (May’17 and Oct’17)
			(2 - 3)	Soft (only May’17)

See backup slides
for complete table

Future of the DQW SPS-series prototypes

NEXT TESTS FOR PERFORMANCE VALIDATION TOWARDS LHC-SERIES

Test I: Cryogenic RF test **with another HOM filter** (in preparation for Test II)

Test II: Cryogenic RF test **with 2 HOM filters** (LHC configuration)

Test III: Cryogenic RF test **with new HOM filter** (available by Spring 2019)

- Use for: field mapping, multipoles, development of RF feedback control system of tuner, multipacting conditioning studies, etc.

EXPLORATION OF ULTIMATE RF PERFORMANCES *(under consideration)*

- **Electropolishing on cavity** (KEK conducted first trials on DQW PoP-series)

  Challenges: cathode shaping for uniform removal; bubble trapping in corners.

- **N-infusion**

  Limited impact expected: no R_{BCS} inversion observed in low-frequency cavities; R_{res} is main contributor to DQW surface resistance.

- **Flux trapping studies**

  Limited impact expected: $R_{res}^{(H\text{-field})}$ is already small for low-frequency cavities.

SUMMARY

MATURE DESIGN OF DQW+HOM MEETS REQUIREMENTS

- DQW + HOMs **delivers 4.7 MV** before quench (38% margin). [5.9 MV w/o filter.]
- **Cryogenic load <5 W** (at 3.4 MV) with pretty low Rs (10 nOhm at low field).

  - ✓ **Sound and adequate EM design** of cavity + HOMs.
  - ✓ Demonstrated successful **manufacture by industry**
  - ✓ Proved sufficiency of **standard SRF surface treatments**

    (*But note:* HOMs should receive same treatment as any other SRF cavity.)

SOME MARGIN FOR IMPROVEMENT

- **Large peak fields** reached – at quench field (4.7 MV), max. Bp of 106 mT (cavity).
- *But* **still not as high** as values reached by **other BCPed Nb cavities** (see backup).

LIMITATIONS

- Quench, likely a **thermal quench in HOM filter**, limits CW operation.
- **Recurrent multipacting** band **below 0.5 MV**.

FUTURE

- **Activities for performance improvement and understanding** under discussion.
- **Translate experience** to LHC-series DQW, RFD and eRHIC DQW cavities.
- Promising **new HOM filter** coming (see J. Mitchell's talk).

Thanks for your attention

Acknowledgements

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Funding agencies

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[2] S. U. De Silva, H. Park, J. R. Delayen, and Z. Li, *RF tests of the RF-Dipole prototype crabbing cavities for LHC high luminosity upgrade*, in Proceedings of the 18th International Conference on RF Superconductivity (SRF'17) (JACoW, Lanzhou, 2017), pp. 509–511.

Back-up

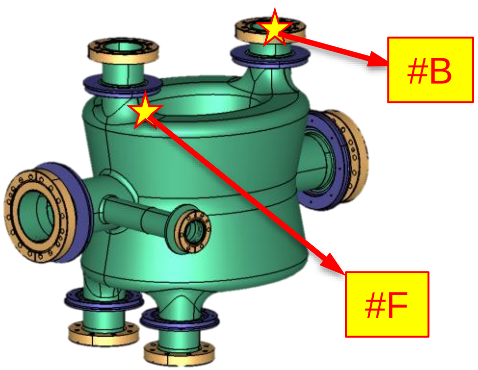
SUMMARY: *DQW SPS-series prototype tests*

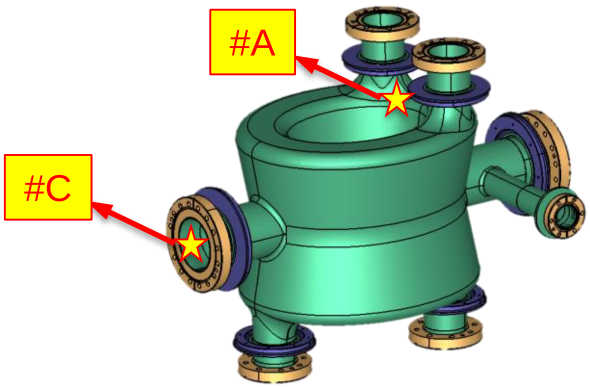
DQW SPS-series prototypes built by Niowave Inc. and JLab. HOM filter on loan from CERN. All tests performed in JLab.

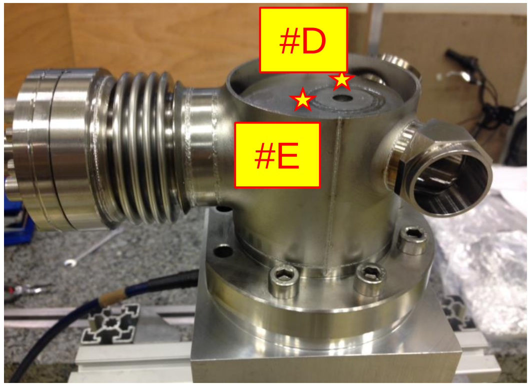
Test	Assembly	Surface preparation		Max Vt (MV)	FE (MV)	Q0, low	Q0,nom [P (W)]	CX
		Cavity	HOM filter					
Feb’17	DQW01	Bulk BCP, 600C, light BCP, HPR, 120C	N/A	5.9	4.1	1e10	6e9 [4.5]	#B-2 #F-4
May’17	DQW01+HOM01 Flange set #b	None	Flash BCP (on hook); rinse	2.8	n/a	1e10	n/a	#B-5 #D-7 #E-8
Jun’17	DQW02	Bulk BCP, 600C, light BCP, HPR, 120C	N/A	5.3	3.3	9e9	5e9 [5.4]	#A-567 #F-4
Sep’17	DQW02	Light BCP, HPR	N/A	5.3	4.1	1e10	6e9 [4.5]	#C-1 #A-7
Oct’17	DQW02+HOM01 Flange set #a	Light BCP, HPR	Flash BCP (on hook); rinse	3.6	n/a	1e10	6e9 [4.5]	#F-4 #D-7 #E-8
Jan’18	DQW02+HOM01 Flange set #a	None	100 um BCP, 600C, light BCP, rinse	3.1	2.6	1e10	n/a	N/A
May’18	DQW02+HOM01 Flange set #a	HPR, 120C	Rinse, 120C	4.7	3.2	1e10	7e9 [3.8]	None
Jul’18 (testing anomaly)	DQW02+HOM01 20mm NbTi spacer Flange set #a	HPR, 120C	Rinse, 120C	5.9	None	8e9	5e9 [5.4]	N/A
Sep’18	DQW02+HOM01 20mm NbTi spacer Flange set #a	HPR, 120C	None	5.1	2.7	9e9	5e9 [5.4]	#E-8

SUMMARY: *DQW SPS-series prototype tests*

Thermosensor labels:







Coupling evolution for test probes

Assembly	Test	*External Q for input probe,* $Q_{ext,IC}$ (aka Q_1)	*External Q for pickup probe,* $Q_{ext,PC}$ (aka Q_2)
DESIGN	CST	2e9	8e11
NWV-DQW-001	Warm	1.92e9	1.77e12
	Cold Feb'17	2.07e9	1.60e12
NWV-DQW-002	Warm	1.83e9	1.19e12
	Cold Jun'17	2.05e9	1.78e12
	Cold Sep'17	1.83e9	1.20e12
NWV-DQW-001 + 1HOM	Cold May'17	2.10e9	1.47e12
NWV-DQW-002 + 1HOM	Cold Oct'17	1.93e9	1.21e12
	Cold Jan'18	n/a	n/a
	Cold May'18	2.12e9	1.21e12
	Cold Jul'18	1.93e9	1.04e11 (anomaly)
	Warm	n/a	6.28e12
	Cold Sep'18	2.08e9	2.74e12

Multipacting predicted			*Found during tests w/o filter*	
MP band [MV]	Region	Code	MP voltage [MV]	Comments
(0.26)	Cavity waist	CST	0.17, 0.2	Hard. Conditioned 1.5h at 10-20 W input power before first breach through. Every quench will cause cavity to drop into this zone for about 30 minutes. Found for every test.
(0.1 – 0.5)	Cavity waist	ACE3P		
(1.06)	Cavity-small port	CST	1.1	Soft
(1.0 – 2.5)	Waist	CST	1.9, 2.3	Soft
(0.8 – 3.5)	Lunette	CST	1.9, 2.3, 3.0	Soft
(1.6 – 3.0)	Cavity-beam port Cavity-small port	ACE3P	1.9, 2.3, 3.0	Soft
(4.0 – 4.5)	Lunette	ACE3P	4.5	Soft. Quenched into this MP band for a few minutes.

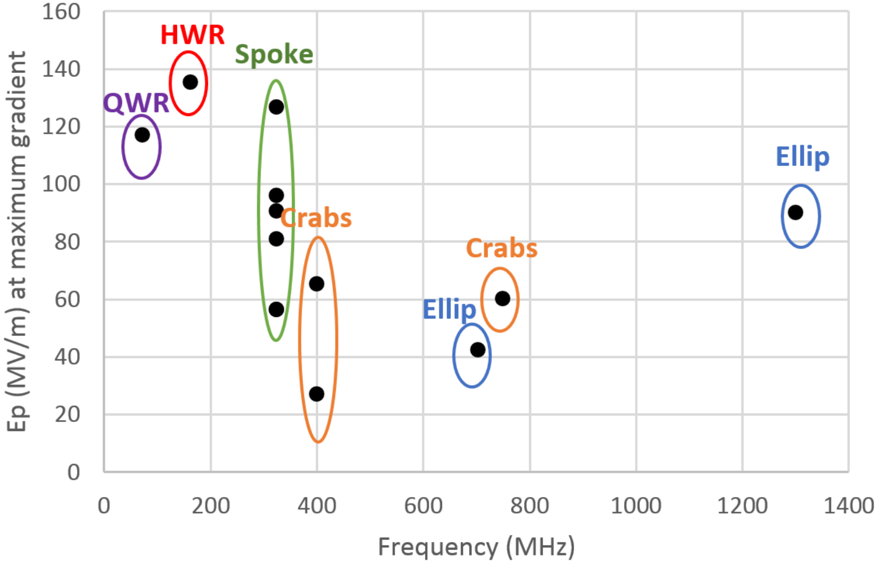
Predicted			*Found during tests with or w/o filter*	
MP band [MV]	Region	Code	MP voltage [MV]	Comments
(0.26)	Cavity waist	CST	0.17, 0.2	Hard.
(0.1 – 0.5)	Cavity waist	ACE3P		
(2.12)	HOM stub	CST	(1.8 - 2.3)	Soft (May’17 and Oct’17)
			(2 - 3)	Soft (only May’17)

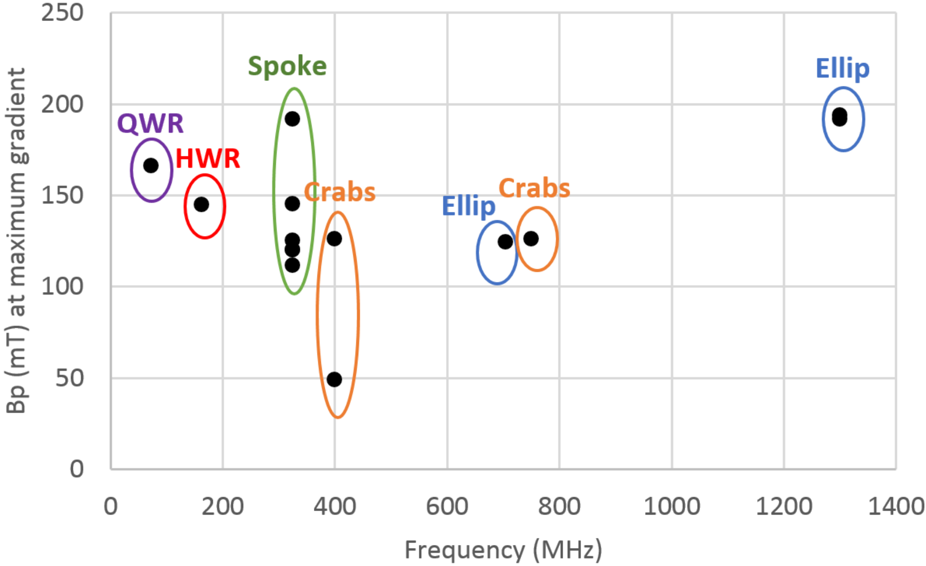
Test summary: Lorentz force detuning

- Cold test frame does not fully reproduce boundary conditions of DQWs in cryomodule. Expected LFD for DQW in cryomodule is -40 Hz/(MV2)??. Measured LFD during cold tests is about 500 Hz/(MV2)??
- Removed rods fixing capacitive plates to stiffening frame for test on Jan’18.

  See further reduction of frequency, as expected, if capacitive plates are not longer fixed.

Comparison to other cavities





- Magnetic field level comparable to the highest values reached by other SRF cavities following a BCP-based surface treatment (see next slide).

Survey – highest peak fields reached by SRF cavities

Cavity type	Cavity name	No. cells	beta	Freq f (MHz)	Temp T (K)	Eacc (MV/m)	Ep/Eacc (--)	Hp/Eacc (mT/MV/m)	Ep (MV/m)	Hp (mT)	Note	Project
Spoke	Spoke012	1	0.14	325	2.3	18.13	5	6.9	90.65	125.10		CADS injector
				325	4.2	16.2	5	6.9	81	111.78		CADS injector
Spoke	Spoke021	1	0.24	325	2.0	12.8	4.4	9.4	56.32	120.32		CADS injector
				325	4.0	12.8	4.4	9.4	56.32	120.32		CADS injector
Spoke	SSR1	1	0.215	325	2.0	33	3.84	5.81	126.72	191.73		Project-X
				325	4.0	25	3.84	5.81	96	145.25		Project-X
TESLA, large grain	AC155	9	1	1300	2.0	45	2	4.26	90	191.70		European X-FEL
Elliptical	PAV007	1	1	1300	2.0	45.6				194.00		N2 infusion - 120 C bake
Elliptical	ERL704	5		703.75	2.0	21.5	1.97	5.78	42.355	124.27	check Bmax	ERL
HWR	HWR5	1	0.112	162.5	2.0	28.9	4.68	5.02	135.252	145.08		PXIE
QWR	QWR72	1	0.077	72.75	2.0	23.3	5.2	7.6	117	166	Pulsed, admin. limit	ANL ATLAS intensity upgrade
	QWR56	1		56.3	4.0							RHIC "passive" RF bunch compre
RF dipole	RFD	1	1	750	2.0	2.7	4.29	9.3	60	126		MEIC
	RFD PoP	1	1	400	2.0	6.9	3.9	7.13	26.9	49		HL-LHC
DQW	SPSDQW1	1	1	400	2.0	5.9	11.0588	21.4	65.2469	126.26		HL-LHC

- Shows peak surface electric field and peak surface magnetic field at the maximum accelerating (deflecting for the crab cavities) gradient reached by different SRF cavities.
- Only cavities with best performance found in literature (best here means highest peak fields, not highest Q0).
- Cavities following **EP-based** surface treatment are highlighted in **blue.** The other cavities followed a BCP-based treatment.

NWV-DQW02+CERN-HOM01 + 20mm NbTi spacer

Temperature monitoring during test of Sep’18 at JLab

- CERNOX thermosensors in 8 different locations.
- CX#3 signal not available during Vt sweep.
- CX#8 follows Vt until it gets lost; however, CX#7 did not registered any ΔT.
- Other CERNOX do not show any significant temperature increase associated with Vt.