DQW cold testing

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Cryogenic RF (2K) Performance Requirements

Eng. Spec. EDMS 1389669 [1]

- ***Resonant frequency of crabbing mode at 2 K*** **400.79 MHz**

  RF surface resistance: $R_S = \underbrace{R_{BCS}(\omega^2)}_{1\ n\Omega} + R_{res,H}(\sqrt{\omega})$

- ***Nominal deflecting voltage V_t*** **(3.4 MV) + 20% margin** **≥ 4.1 MV**

- ***Dynamic heat load for dressed cavity at 2 K and 4.1 MV*** **≤ 10 W**

  $Q_0 \geq 5.4\text{x}10^9$ for operation at 2 K and 3.4 MV

  (For DQW SPS-series, R_t/Q = 430 Ω and G = 87 Ω, allows R_S = 16 nΩ)

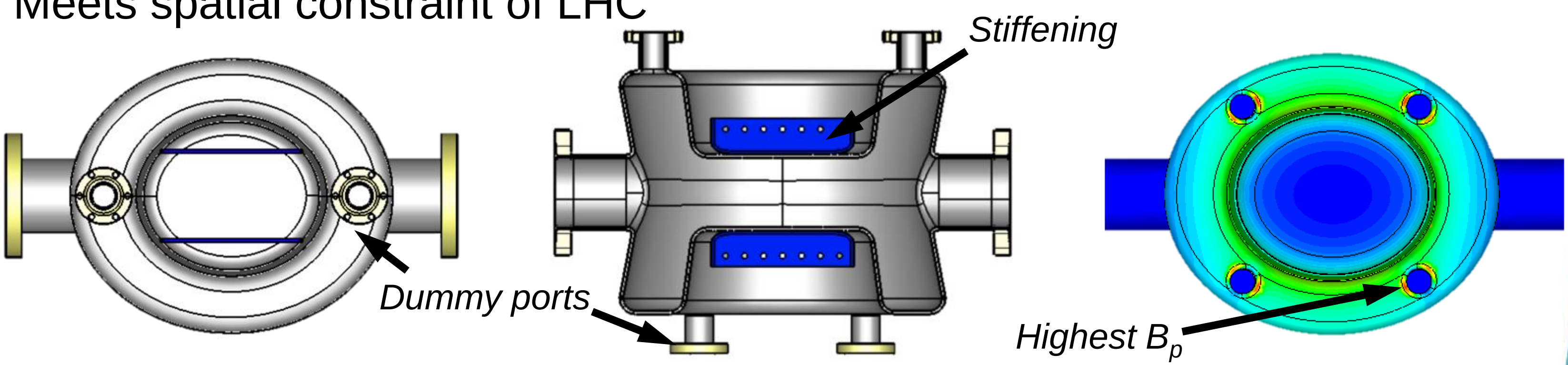
PoP-series DQW prototype

SCOPE

- **Validation of DQW concept** (cryogenic RF test)
- Also used for: testing tuning system, first electropolishing attempt, measurement of multipoles, etc.

DESIGN

- Only **bare cavity** with stiffening frame, no couplers, no helium tank
- Dummy ports, **highest Bp** located **in port blend**
- Meets spatial constraint of LHC



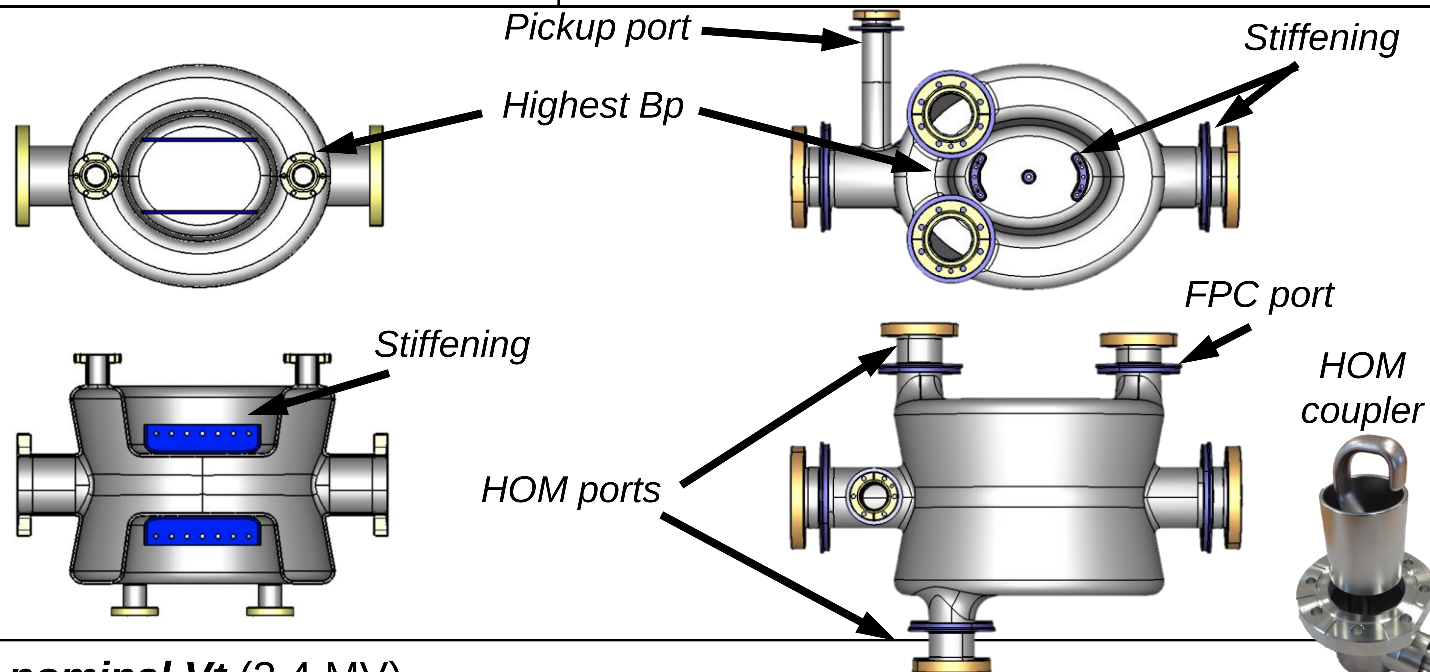
FABRICATION AND TESTING

- One (1) fabricated within US LARP by Niowave; tested at BNL and CERN

CRYOGENIC (2K) RF PERFORMANCE

- **Exceeded nominal Vt** (3.4 MV) with **38% margin** (max. reached = 4.6 MV)
- RF surface resistance of **22 nOhm at 1.9 K** leading to $Q_0 = 4x10^9$

Design evolution of the HL-LHC DQW crab cavity[2]

	PoP-series [3]	**SPS-series** [4]
Scope	**DQW concept validation** Only **bare cavity**	**Fully adequate for beam operation** (input power, HOM damping, integration) **Full design of cryomodule** with two cavities
Design evolution 1) Port size 2) Lower Bp by blend&racetrack 3) Compatible with cryomodule		
EM properties at nominal Vt (3.4 MV)		
RF freq. (MHz)	400	400
Max. Bp (mT)	85.4 / --	72.8* / 56.6
Max. Ep (MV/m)	36.5 / --	37.7 / 29.0
Rt/Q (Ohm)	406	429
G (Ohm)	85	87

* 11% lower than PoP, highest H in cavity body

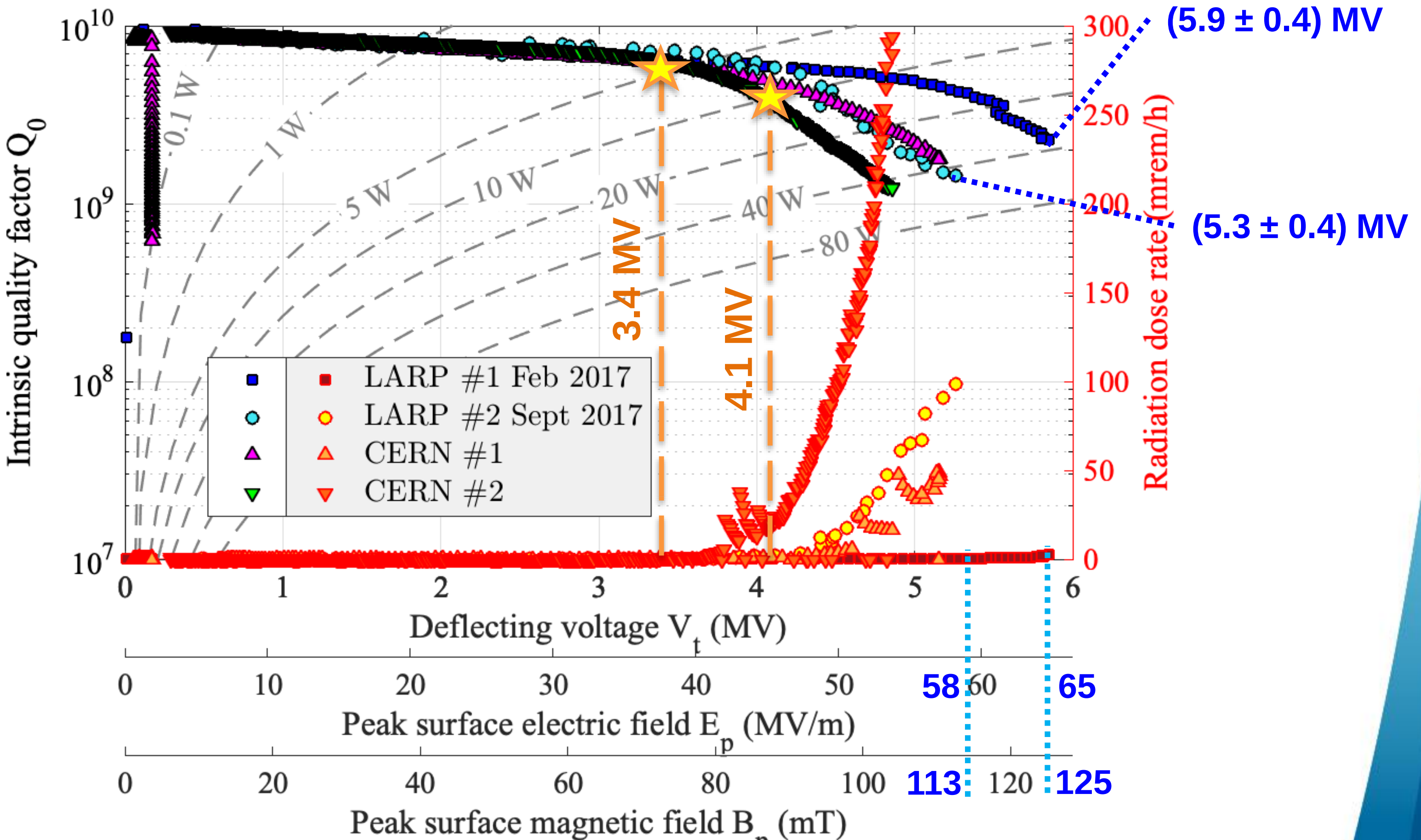
DQW SPS-series cavities

- Two (2) bare cavities built within US LARP at Niowave and JLab.
  1) Assist **fabrication, tuning**
  2) **Investigate limited 2K RF performances** of **DQW + HOM couplers**
     (HOM couplers provided by CERN.)
- Two (2) cavities built in-house by CERN, installed in cryomodule and tested with proton beam of SPS.

All the cavities following **BCP-based** standard **surface treatment** procedure: bulk BCP, 10h 600C, light BCP, HPR, 24h 120C.

Cryogenic (2K) RF performance of bare DQWs

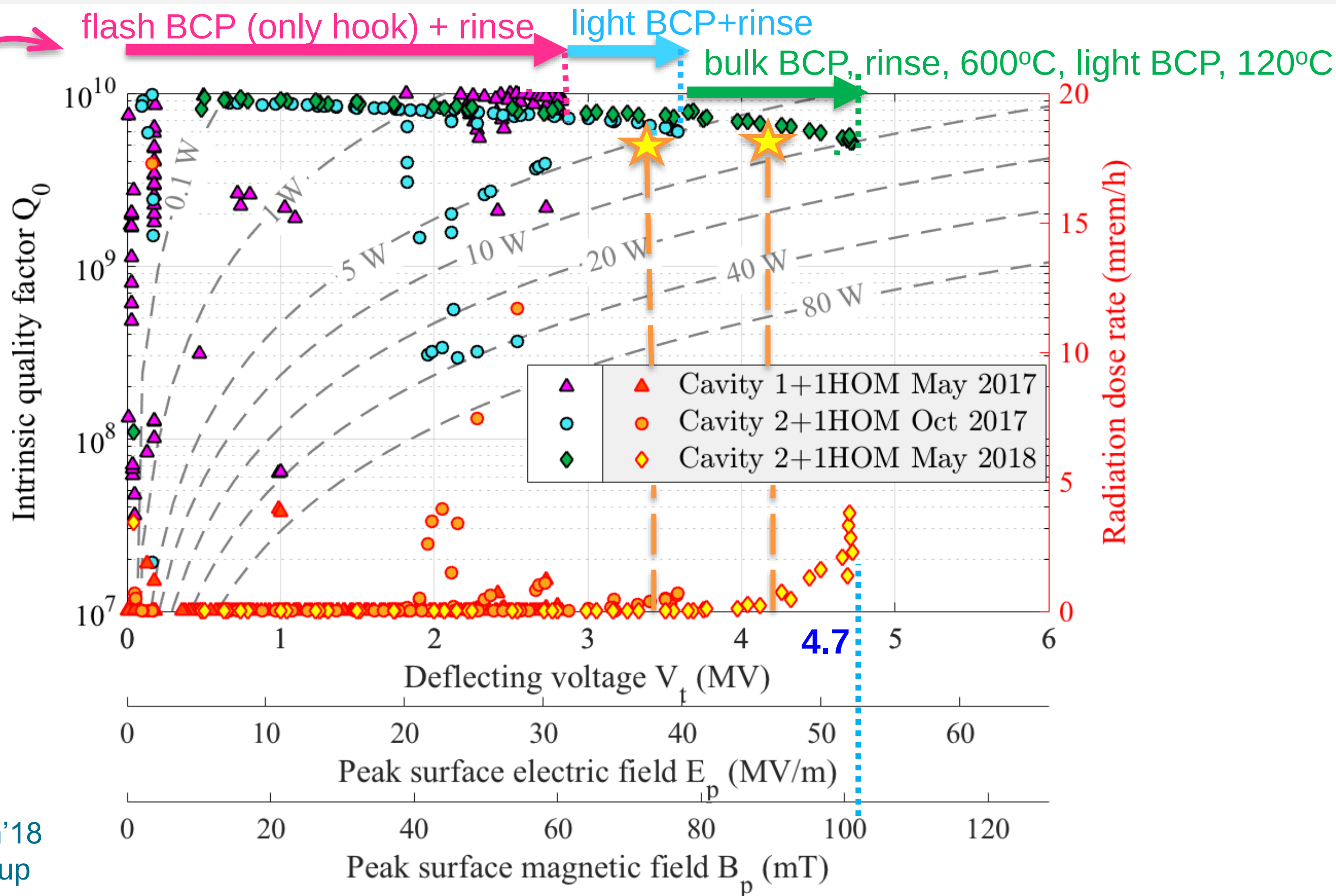
- **Exceeded nominal Vt** (3.4 MV) **with** 40% **margin**; **P < 10 W** at 4.1 MV **as required**
- **Excellent** performance of **bare cavities** beyond nominal (up to 5.9 MV).
  - Large peak fields reached (~ 30 MV/m TESLA-type cavity)
  - FE onset at Vt = 4.1 MV (above nominal deflecting voltage)
  - Pretty low surface resistance (9 nOhm)



Cryogenic (2K) RF perf. of DQW + HOM coupler

STUDY I – EFFECT OF SURFACE TREATMENT

- **Early quench** of CERN#1 **with** 3 **HOM couplers;** also for LARP#1 with 1 HOM coupler**.** HOM couplers had **only received flash BCP + rinsing**.
- *Lesson learned:* **HOM couplers** should receive **same surface treatment as** any other **SRF cavity**.
- LARP#2 + 1 HOM coupler **reached 4.7 MV** (largest Vt to date in any DQW equipped with HOM).
- **No evidence** of **High-Field Q-Slope (HFQS).**



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

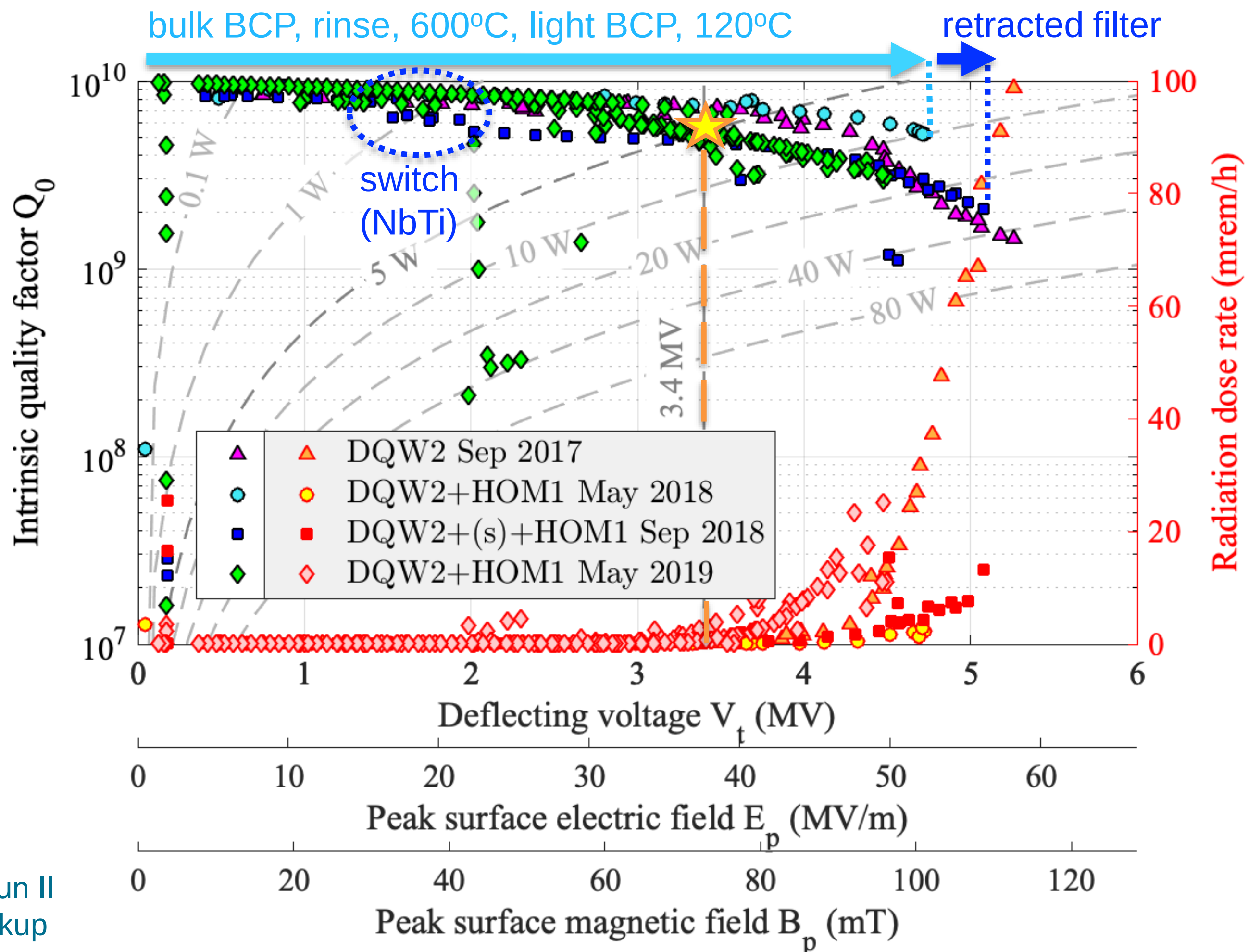
Cryogenic (2K) RF perf. of DQW + HOM coupler

STUDY II – DISCRIMINATE QUENCH FROM CAVITY OR COUPLER

- **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.



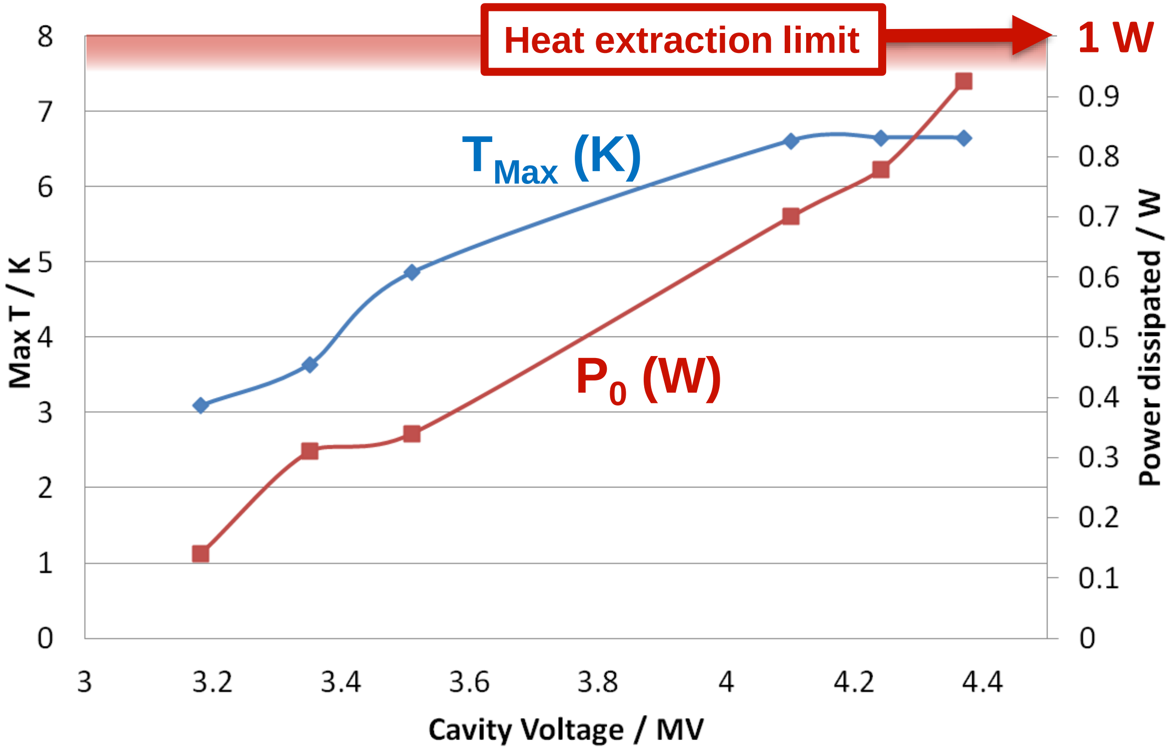
Jul'18 and Sep'18 run II not shown: see backup

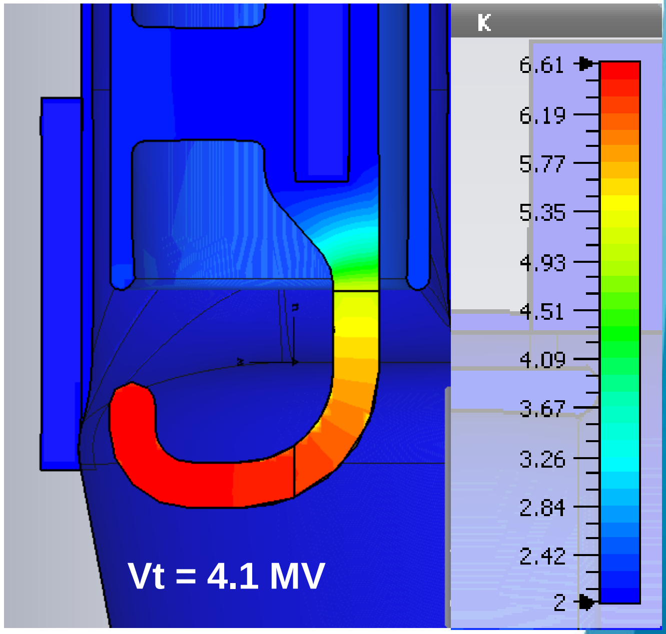
FY2018: high performance program

Why would the HOM coupler 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]





Cryogenic (2K) RF perf. of DQW + HOM coupler

STUDY III – LHC CONFIGURATION: MORE THAN ONE HOM COUPLER

- Test in Jul.'19 found **large leakage of fundamental mode** power through the 2nd HOM coupler.
- For next test, the 2nd HOM coupler is installed with **90deg clocking to reduce leakage**.
- **Test at 2K today!**

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

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.)

LIMITATIONS

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

OVERVIEW

NEXT TESTS

LARP #1: - Cryogenic RF test at CERN (benchmarking)

LARP #2: - Test with 2 filters, one rotated to reduce fundamental power leak

- Cryogenic RF test at BNL, field mapping, multipoles

- Electropolishing at KEK (ultimate RF performances)

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

FUTURE

- **Translate experience** to LHC-series DQW, RFD and eRHIC DQW cavities.
- Extend studies of **N-doping** to 400 MHz frequency

Thanks for your attention

Acknowledgements

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REFERENCES

[1] Eng. Spec. EDMS 1389669

[2] S. Verdú-Andrés, et al., *Design of LHC crab cavities based on DQW cryomodule test experience,* Proc. of SRF'19 (Melbourne, 2019), paper THP035.

[3] B. P. Xiao, et al., *Design, prototyping and testing of a compact superconducting double quarter wave cavity*, Phys. Rev. ST Accel. Beams 18, 041004 (2015).

[4] S. Verdú-Andrés, et al., *Design and vertical tests of double-quarter wave cavity prototypes for the high-luminosity LHC crab cavity system*, Phys. Rev. ST Acc. Beams 21, 082002 (2018).

Back-up

Functional Specifications [Eng. Spec. EDMS 1389669]

CRYOGENIC RF (2K) PERFORMANCE REQUIREMENTS

RF and Performance Requirements	Units	DQW	RFD
Resonant frequency of crabbing mode at 2 K [1]	MHz	400.79 ±0.15	
Elastic tuning range	kHz	±150	
V_T —Deflecting voltage at 2 K [2]	MV	≥4.1	
P_{dyn} —Dynamic heat load per cavity at 2 K and 4.1 MV [1, 3]	W	≤10	
LFD —Lorentz Force Detuning coefficient	Hz/MV^2	< 400	≤865
df/dp —Sensitivity to LHe pressure fluctuations	Hz/mbar	≤300	
Pole Symmetry (electrical centre deviation)	mm	≤0.8 [7]	
Field non-linearity (b_3)[4, 5]		< 1500 (TBC[6])	
Qe —Fundamental power coupler external Q	–	5×10^5	
RF power	kW –CW	40 (80 peak)	
Beam clearance	mm	84 ±3 mm	

[1] With all coupler ancillaries
[2] Nominal 3.4 MV plus 20% margin
[3] Assuming $Q_0 \geq 5.4 \times 10^9$ at 2 K and 3.4 MV where $R/Q_{(DQW)}$ = 430Ω and $R/Q_{(RFD)}$ = 430Ω
[4] Preliminary value, which will be confirmed by ongoing studies
[5] Measured using bead pull or wire method
[6] Normalized to 10 MV
[7] Clarification pending

	PoP-series [3]	**SPS-series** [4]
Scope	**DQW concept validation** Only **bare cavity**	**Fully adequate for beam operation** (input power, HOM damping, integration) **Evaluation with beam in SPS** **Full design of cryomodule** with two cavities
EM properties at nominal Vt (3.4 MV)		
RF freq. (MHz)	400	400
Max. Bp (mT)	85.4 / --	72.8* / 56.6
Max. Ep (MV/m)	36.5 / --	37.7 / 29.0
Rt/Q (Ohm)	406	429
G (Ohm)	85	87
Manufactured Cavities		
US LARP	1	2
Manufacturer	Niowave	Niowave + JLab
VT facility	BNL	JLab
HL-LHC WP4	--	2^{+}
Manufacturer	--	CERN
VT facility	--	CERN
VT Results	- **Exceeds nominal Vt** (3.4 MV) with **38% margin** - **22 nOhm**	- **Exceeds nominal Vt** (3.4 MV) with **38% margin** (up to 73% w/o HOM couplers) - **Heat load below 5 W** as required (Rs = 9 nOhm) - **FE onset above nominal Vt** (at 4.1 MV)

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

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)