Individual and vector sum CW operation of X-FEL module in high Ql (6e7) conditions

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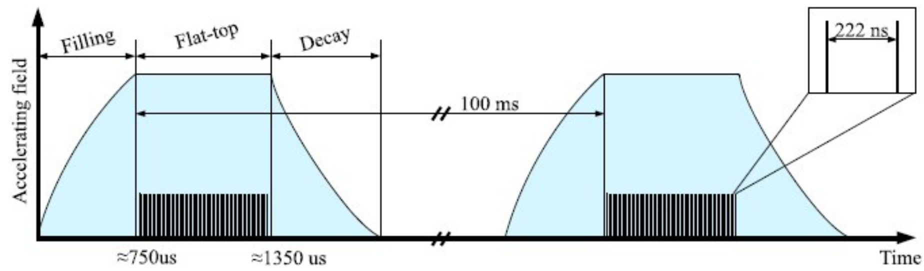
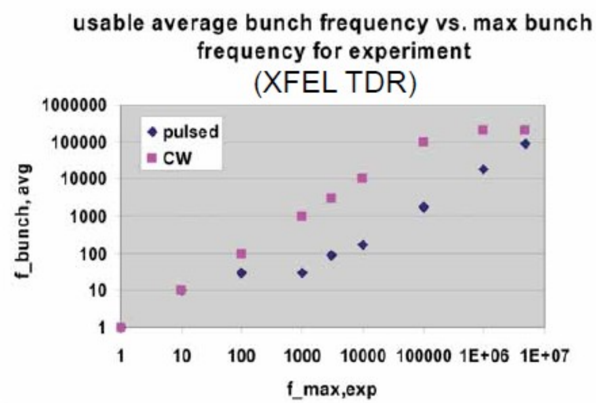
Motivation for high DF studies



- upgrade of the FLASH and/or XFEL,
- relaxed beam patterns for dedicated experiements,
- duty factor increase (limitation comes from the input coupler design – max 2kW of power)



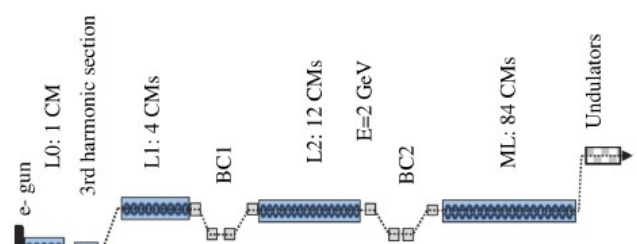
Possible costs drivers for SP -> CW:

•New (dedicated) RF gun,

•Adaptation (extension) of the cryo-plant capacity,

•LLRF system adaptation,

•Dedicated RF power source (for CW mode) – IOT prototype under test.



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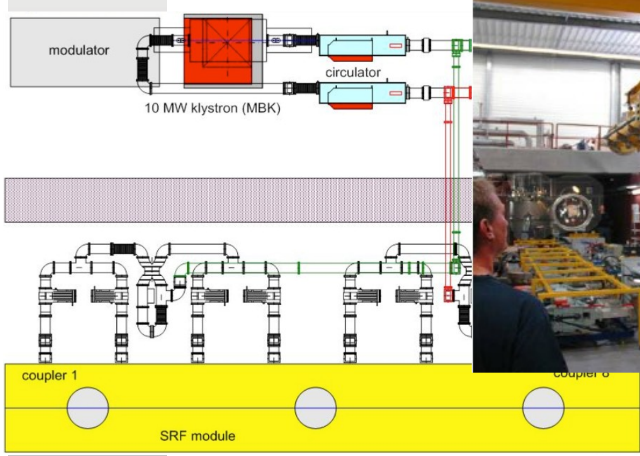
CMTB – CW/LPO teststand

- Tests of XFEL cryomodule have been performed in DESY at Cryo Module Test Bench (CMTB),
- CMTB is single 8 cavities cromodule test stand,
- It is equipped with fully functional cryogenics and high power system suitable for short pulse and CW (LPO) operation



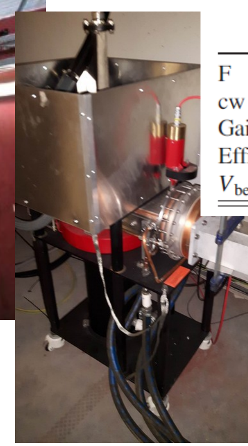
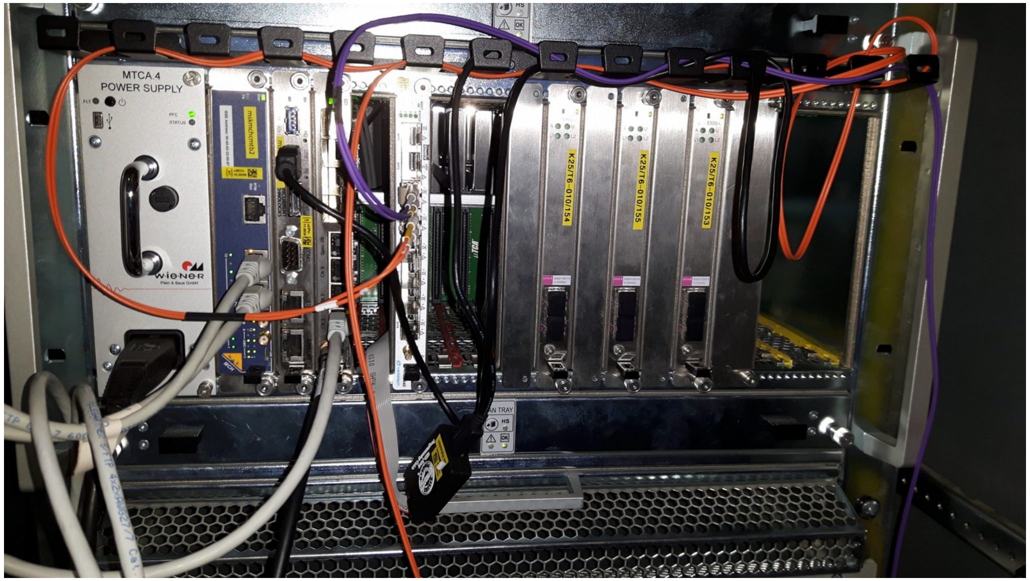


TABLE III. Parameters of IOT prototypes.

	Unit	Specification	Prototype I 2009	Prototype II 2013
F	[MHz]	1300	1300	1300
cw P_{out}	[kW]	120	85	105
Gain	[dB]	>22	22.3	22.7
Efficiency	[%]	>60	54	63
V_{beam}	[kV]	47–49	47–49	47–49

CW - LLRF system setup

- MTCA.4 based LLRF system,
- Hardware setup similar to the XFEL configuration (single module operation),
- PZ16M for the piezo control,
- System can be switched from SP to CW operation with dedicated firmware/server configuration



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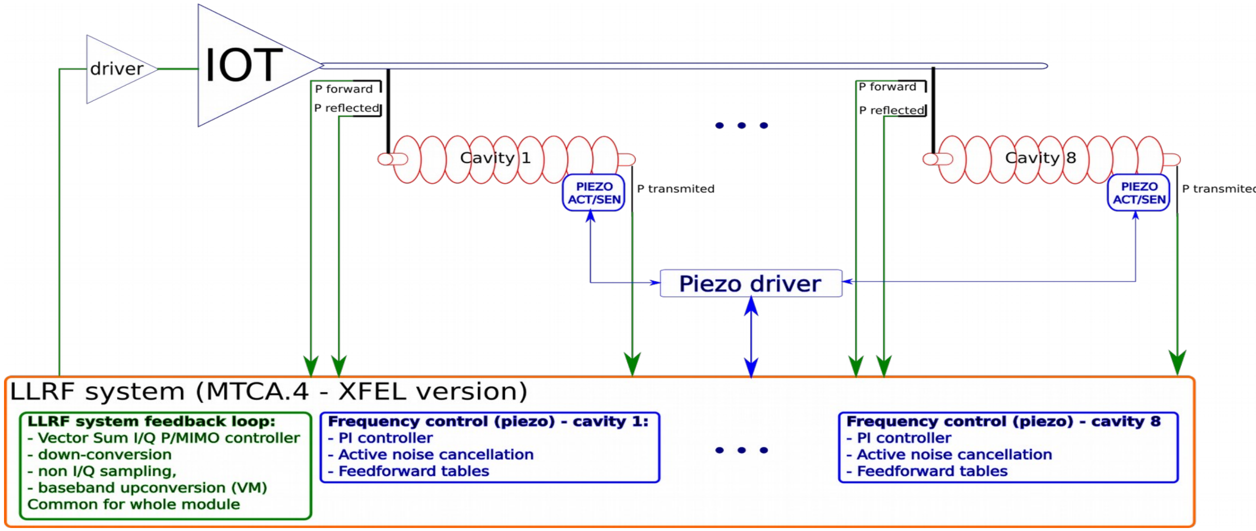
CW - LLRF system setup



- RF field regulation loop:
  - P and MIMO controller,
  - similar to SP with 4,5MHz refresh rate,
- Cavity frequency regulation:
  - DC offset,
  - PI controller (mainly I component used) for low freq (<10Hz) regulation,
  - ANC based solution for persistent microphonics effects reduction

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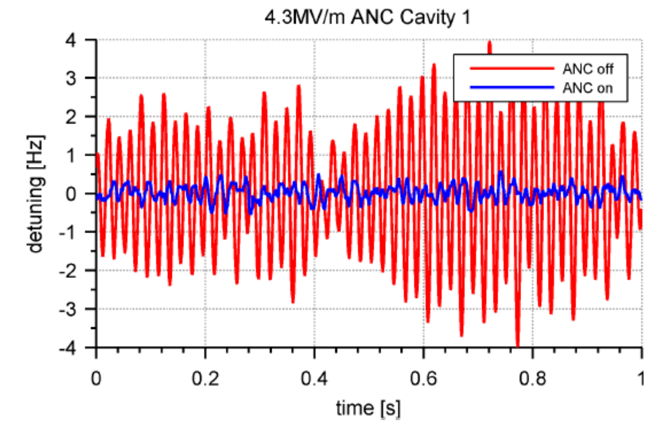
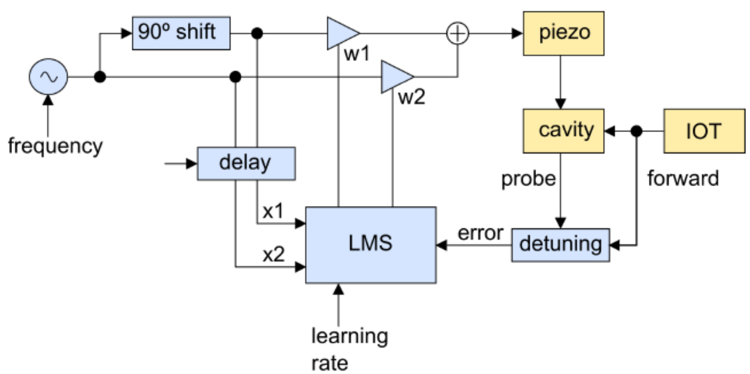
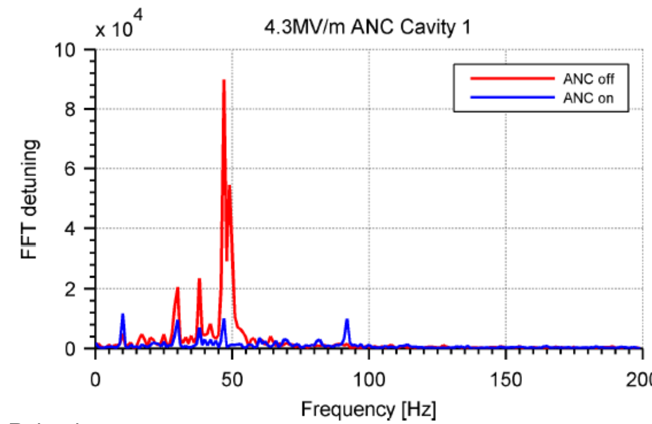
Piezo based microphonics effect suppression

- Active Noise Canceller
  - adaptive algorithm
  - Least Mean Squares
  - implemented in the FPGA
  - no system identification required



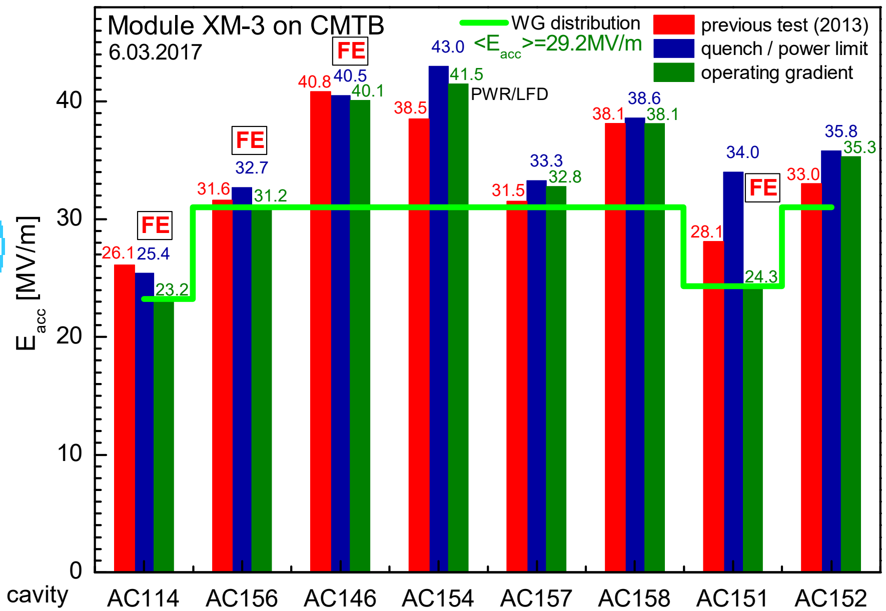




Courtesy R. Rybaniec

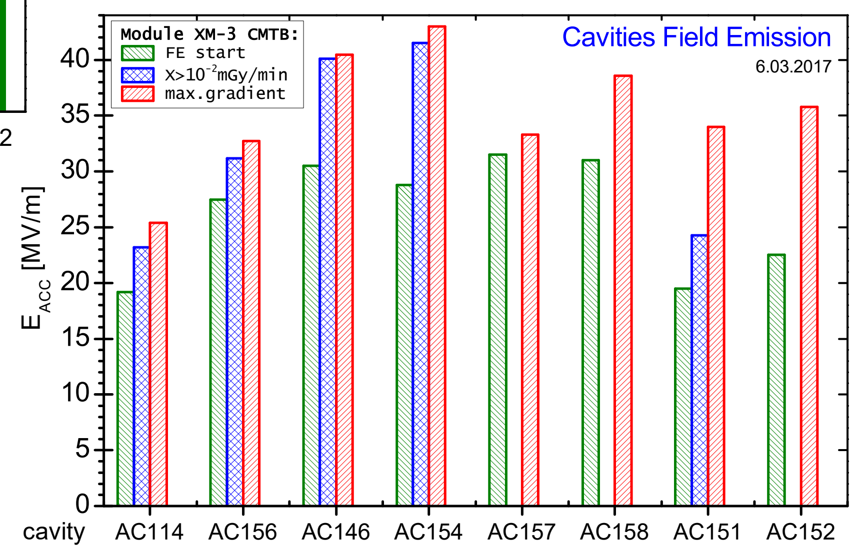
Rybaniec Radosław , Przygoda Konrad, Cichalewski Wojciech *[et all.]*: FPGA based RF and piezo controllers for SRF cavities in CW mode, w: IEEE Transactions on Nuclear Science, IEEE Nuclear and Plasma Sciences Society, vol. 64, nr 6, 2017, ss. 1382-1388, DOI:10.1109/TNS.2017.2687981

XFEL module under test



Courtesy D. Kostin

XFEL module ID: XM-3



Challenges

1. High Ql –> narrow bandwith,
2. Microphonics,
3. Ponderomotive instabilities effect,
4. FPC heating -> Ql change (drop),
5. IOT nonlinearities,
6. Cavities HP signals cross-talk and reflections.

High Loaded Quality factor

- FPC are designed to operate with input power up to 2 kW (pulse operation – range of 400kW),
- Q external needs to be adjusted,

	FLASH	XFEL	CW	CW Max ?
Ql value	3e6	4,6e6	2e7	6e7
Half BW (Hz)	216	142	32,5	11
Input power [kW] (for Eacc = 20MV/m, tuned)	32,6	21,2	5	1,63

- XM-3 after FPC rework shows Ql in the range of 8e7 – for some structures,
- Bandwith becomes really narrow – cavity is more prone to the microphonics,
- Other option (not discussed here) is a Long Pulse Operation (reduce DF to be on the safe side with FPC power limit)…..

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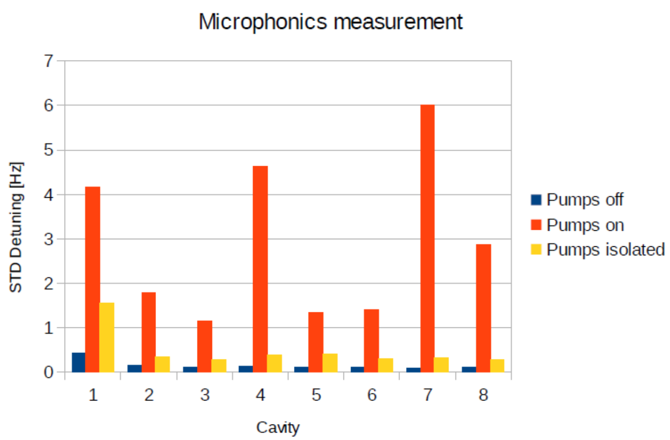
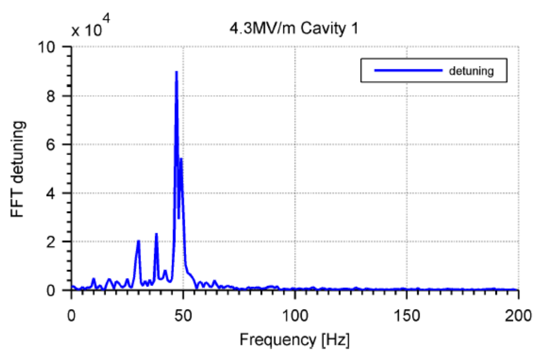
Microphonics





Courtesy R. Rybaniec

- Microphonics main sources
  - Vacum pumps,
  - Helium pressure fluctuation,
- Main frequencies visible on the cavity field
  - 31 Hz
  - 49 Hz
- Microphonics detuning implies more RF power for compensation,
- VS control does not focus on single cav. microphonics.

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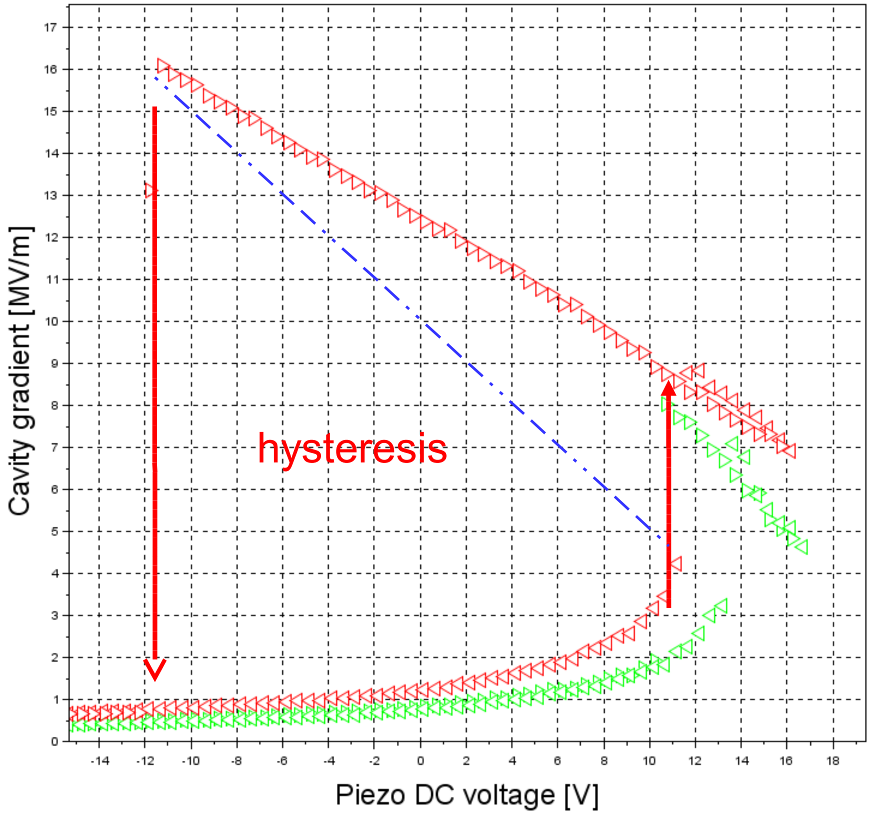
Ponderomotive instabilities in VS regulation

Cavity gradient change in function of the detuning shows hysteresis effect



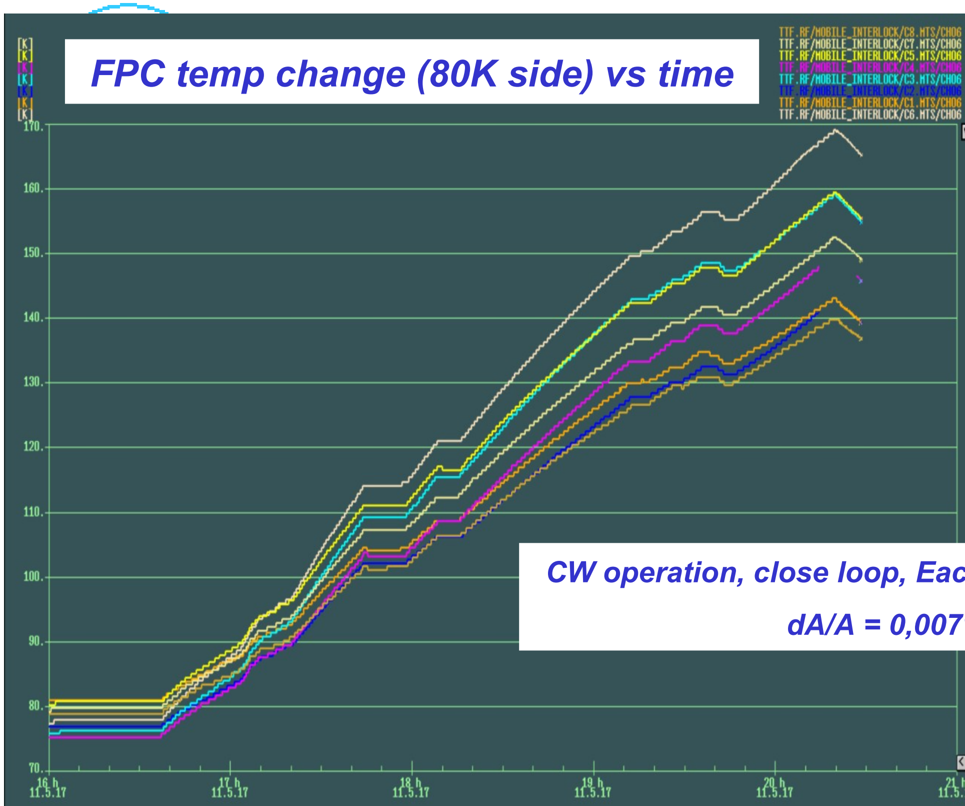
Cav amplitude in function of detuning (measured for different input power SP) (~6Hz/V)

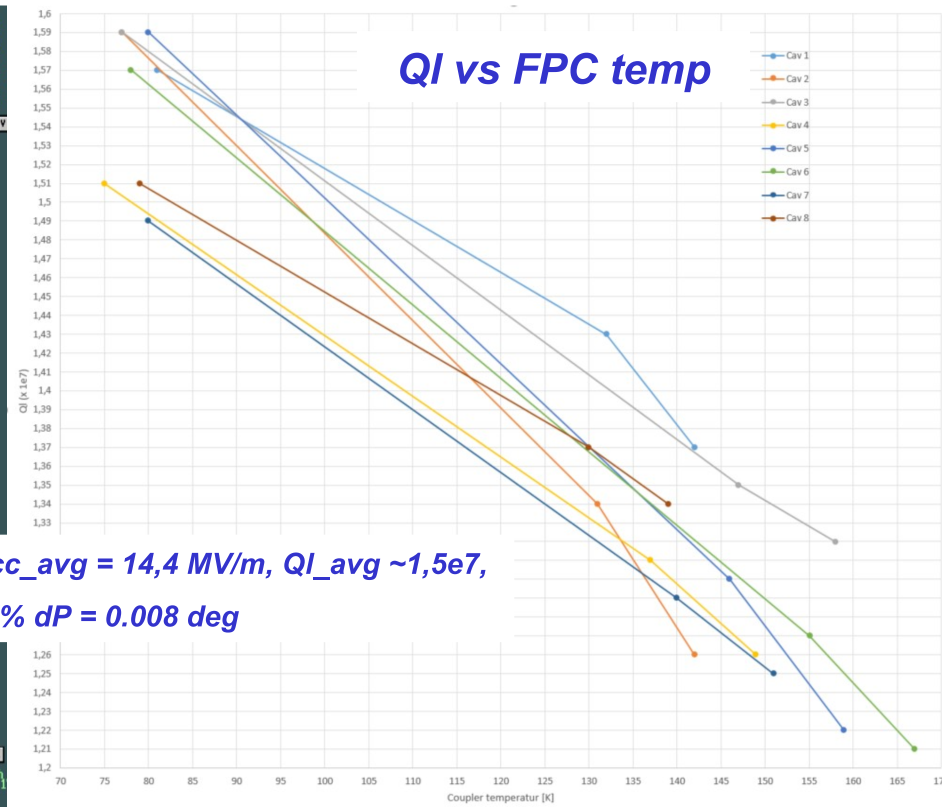
- In case of the Vector Sum control – detuning (and field drop) of single cavity will affect others.
- Initial pretuning of the cavity have to take into account this issue.

Couplers thermal expansion effect

Cavity operation with input power above 3kW leads to the FPC heating,

- Temperature increase results in the Ql change.



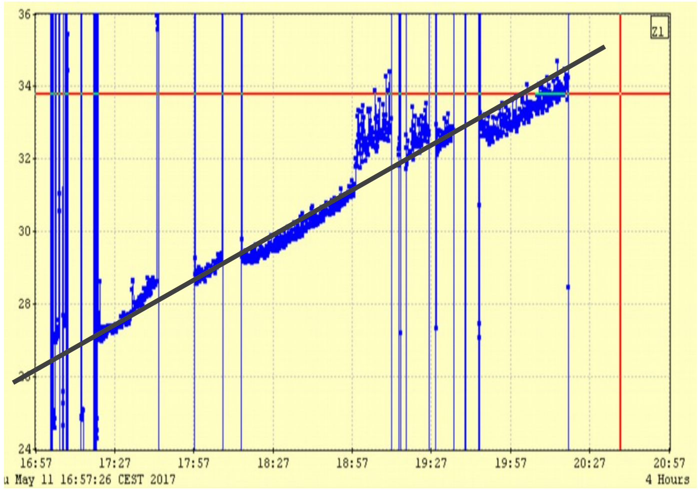


CW operation, close loop, Eacc_avg = 14,4 MV/m, Ql_avg ~1,5e7,

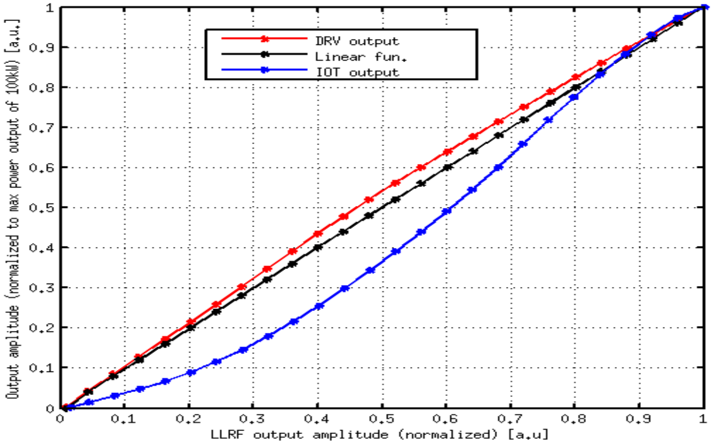
dA/A = 0,007% dP = 0.008 deg

Couplers thermal expansion effect

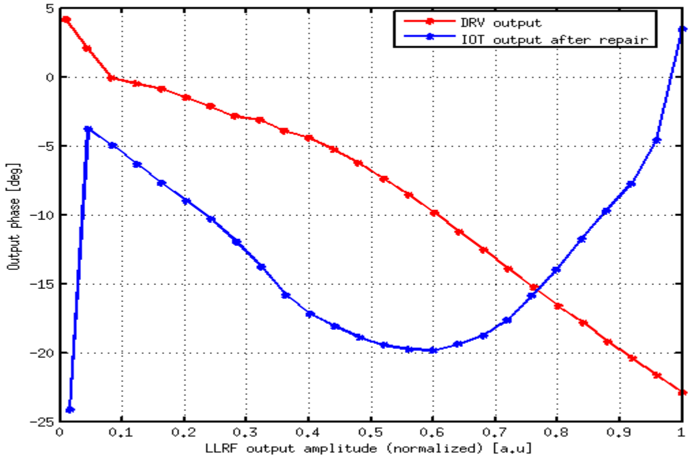
- In close loop VS operation the Ql change is being compensated by the input power increase



IOT output power level during the study period



- IOT change → phase shift (due to nonlinearity) this can impact the detuning estimation and piezo feedbacks,
- conditions are changing but the VS regulation has been better than XFEL spec.



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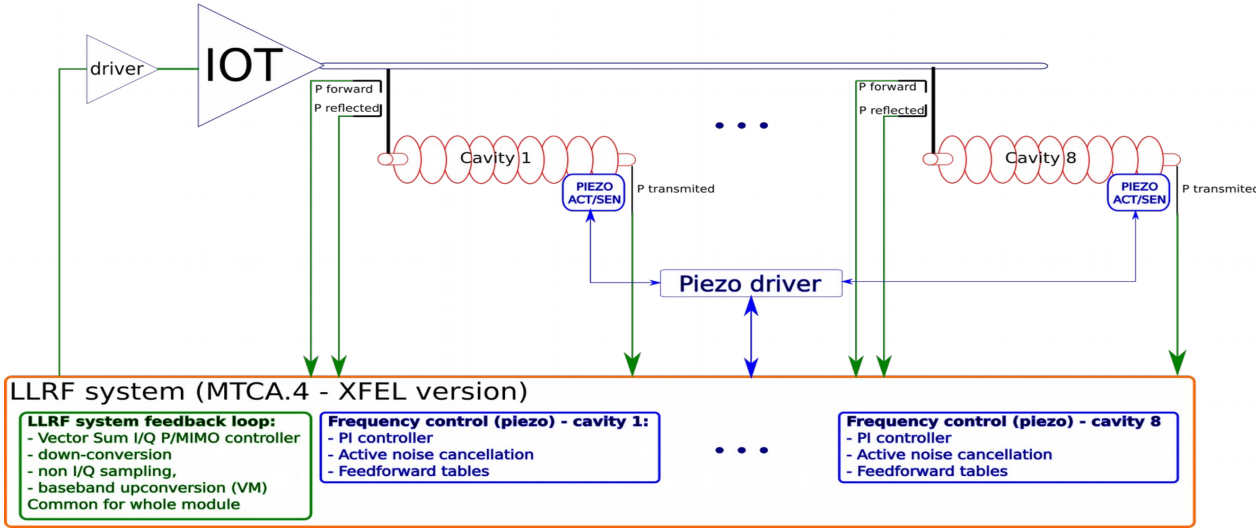
CW - LLRF system setup



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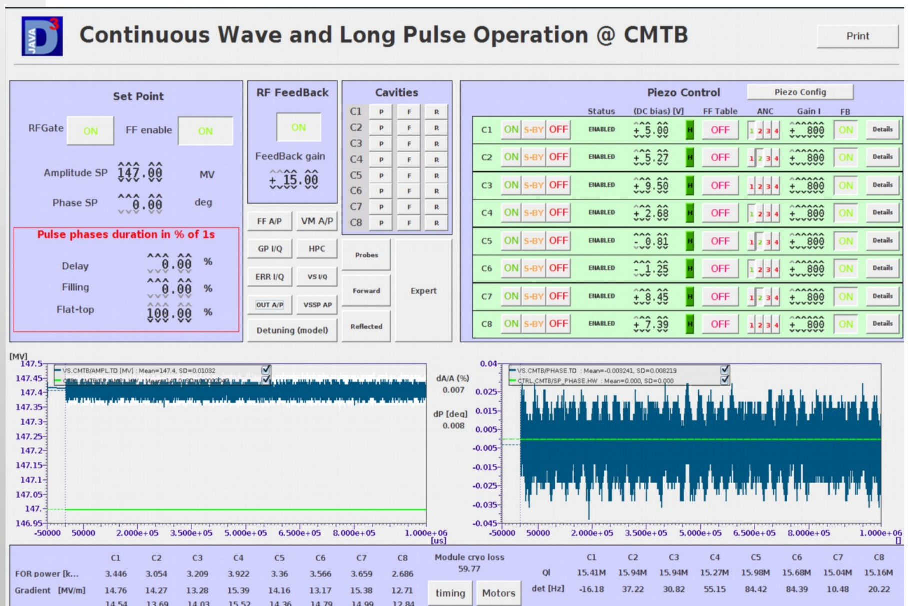
QI ~1,5e7 operation

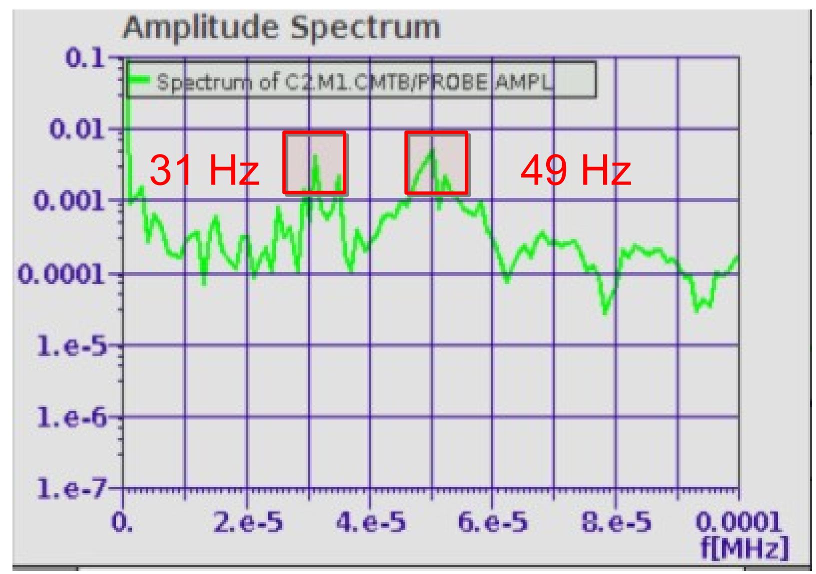
Close loop CW operation:
-Proportional RF feedback,
-Piezo I controller
-ANC filters for some resonators (mainly 31Hz & 49 Hz),
-„cold couplers" QI readout:

	C1	C2	C3	C4	C5	C6	C7	C8
QI	15.35M	15.91M	15.93M	15.19M	15.99M	15.74M	14.94M	15.15M

-Achieved performance:

dA/A = 0.007% (XFEL sp. 0.01%) dP = 0.008 deg (XFEL sp. 0.01)





Amplitude signal FFT (cav 2)

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Cavities Ql adjustment

	After			Before		
Cav	Ql	Pfwd [W]	Eacc [V/m]	Ql	Pfwd [W]	Eacc [V/m]
1	2,80E+07	8,72E+02	1,00E+07	1,53E+07	1,60E+03	1,00E+07
2	1,95E+07	1,25E+03	1,00E+07	1,59E+07	1,54E+03	1,00E+07
3	2,16E+07	1,13E+03	1,00E+07	1,59E+07	1,54E+03	1,00E+07
4	2,00E+07	1,22E+03	1,00E+07	1,51E+07	1,62E+03	1,00E+07
5	1,90E+07	1,28E+03	1,00E+07	1,60E+07	1,53E+03	1,00E+07
6	1,80E+07	1,36E+03	1,00E+07	1,57E+07	1,56E+03	1,00E+07
7	1,70E+07	1,44E+03	1,00E+07	1,49E+07	1,64E+03	1,00E+07
8	1,78E+07	1,37E+03	1,00E+07	1,52E+07	1,61E+03	1,00E+07
	Sum	9,92E+03			1,26E+04	
	Expected input pwr diff.		2,69E+03	21%		

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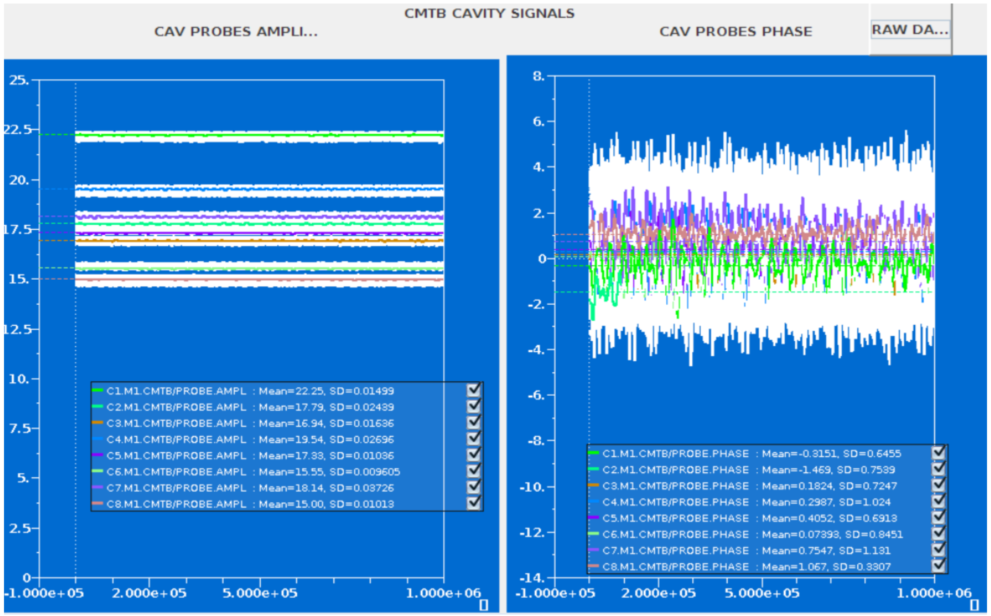
Results for high gradient ~18MV/m (avg)

Controllers configuration:
-Proportional RF feedback,
-Piezo I controller
-ANC filters for some resonators

dA/A = 0.011%
dP = 0.010 deg

Cav	Gradient [MV/m]	dA/A [%]	dP [deg]
1	22,20	0,067	0,65
2	17,80	0,137	0,75
3	17,09	0,096	0,72
4	19,68	0,137	1,02
5	17,35	0,059	0,69
6	15,70	0,062	0,85
7	18,40	0,205	1,13
8	15,07	0,068	0,33



- *Individual cavities performance exceeds field regulation thresholds,*
- *VS control does not focus on the individual cavity regulation*

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Single cavity operation – cavity 3

Cavity data:

ID: AC146
Quench level: 40.5 MV/m
Radiation FE start level: ~30 MV/m,
Main microphonics freq.: 31, 49 Hz

Gradient: 18 MV/m

-RF feedback ON, proportional gain of 8,
-Piezo Integral Feedback ON,
-ANC OFF
Achieved VS regulation accuracy:

dA/A = 0.015% **dP = 0.017 deg**

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Single cavity operation – cavity 3

Gradient: 22 MV/m

-RF feedback ON, proportional gain of 12,
-Piezo Integral Feedback ON,
-ANC ON (31Hz & 49Hz),
Achieved VS regulation accuracy:

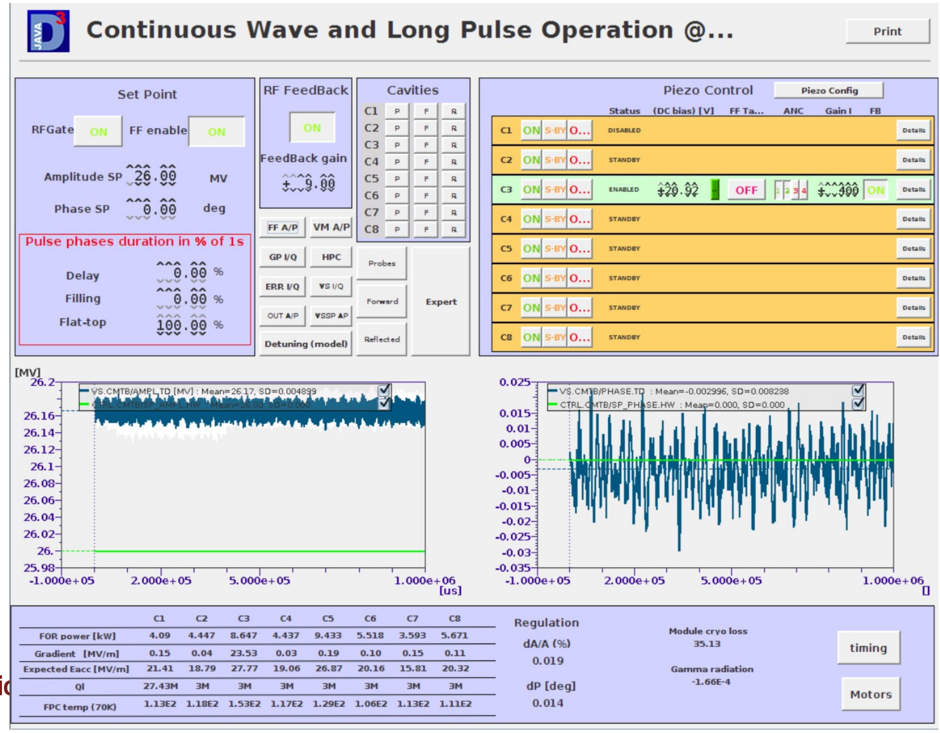
dA/A = 0.018%   **dP = 0.016 deg**

Gradient: 23,5 MV/m

-RF feedback ON, proportional gain of 9,
-Piezo Integral Feedback ON,
-ANC ON (31Hz & 49Hz),
Achieved VS regulation accuracy:

dA/A = 0.019%   **dP = 0.014 deg**

- tested up to the ~23,5 MV/m level,
- quench level not reached (40MV/m),
- High input power needed to achieve higher Eacc (Ql 2,2e7) – fast FPC temp increase,
- during gradient increase – strong oscillations of ~168Hz observed (cavity mechanical mode).



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VS operation (high Ql)

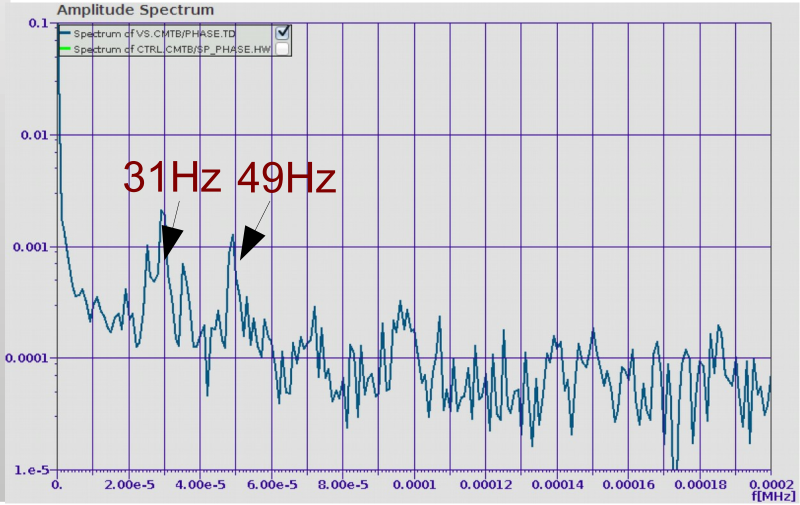
	C1	C2	C3	C4	C5	C6	C7	C8
FOR power [kW]	1.261	1.449	1.462	1.537	1.331	1.346	1.631	1.439
Gradient [MV/m]	15.99	15.57	7.47	17.24	17.99	17.90	9.91	11.54
Ql	60.87M	60.14M	13.92M	67.44M	59.79M	59.62M	24.72M	24.75M

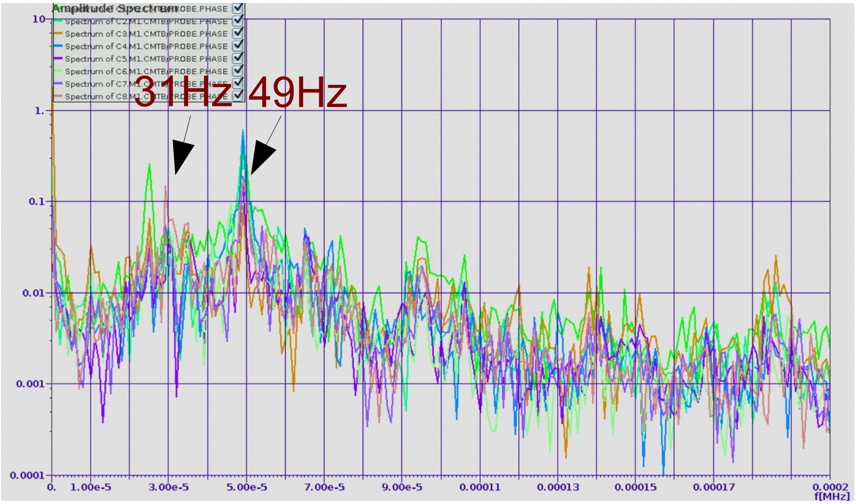
Average Gradient: ~16 MV/m

- RF feedback ON, proportional gain of ~50
- Piezo Integral Feedback ON,
- ANC ON (31Hz & 49Hz) or various structures,

Achieved VS regulation accuracy:

dA/A = 0.007% **dP = 0.008 deg**





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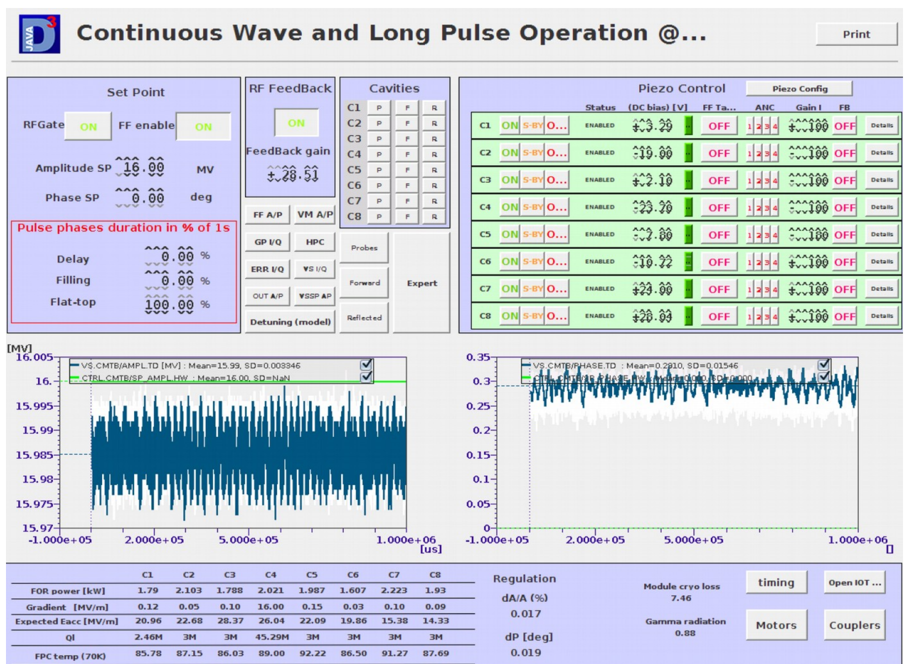
Single cavity operation Ql ~8,2e7 – C#4

Gradient: 16 MV/m

-RF feedback ON, proportional gain of 12,
-Piezo Integral Feedback OFF,
-ANC OFF,
Achieved VS regulation accuracy:

dA/A = 0.017%   dP = 0.019 deg

- Ql adjusted to max. FPC position,
- Achieved Ql of 8,2e7 (HBW ~8 Hz),
- Stable operation with pure RF Feedback,
- Still under investigation – since regulation specs. not fulfilled.



Summary

1. Operation with high Ql (narrow bandwith conditions) still under control in case of VS regulation and single cavity regulation ,
2. Microphonics and LFD can be suppresed using PI feedback and ANC filters (main freqs 31Hz and 49Hz),
3. Ponderomotive instabilities effect taken into account during system configuration and pre-tuning,
4. FPC heating -> Ql change (drop) – compensated by forward power increase but….
5. IOT nonlinearities (if not taken into account) lead to phase shift and can affect detunig calculation and compromise piezo FB activities,
6. Work in progres…..

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Thank You