CW operation of XFEL cryomodule – field regulation performance study for high Ql resonators

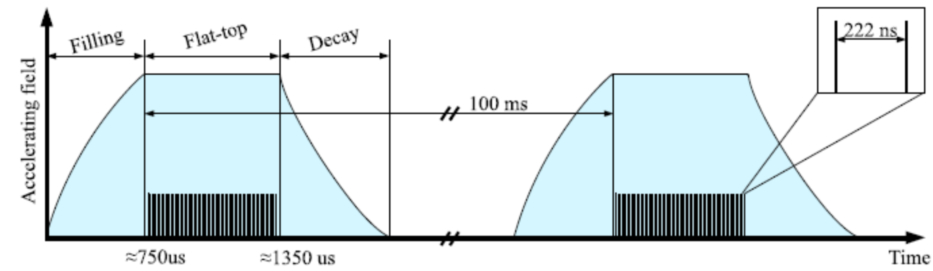
W. Cichalewski, J. Sekutowicz, R. Rybaniec, K. Przygoda, J. Branlard, H. Schlarb, V. Ayvazyan, C. Schmidt, S. Pfeiffer, A. Napieralski

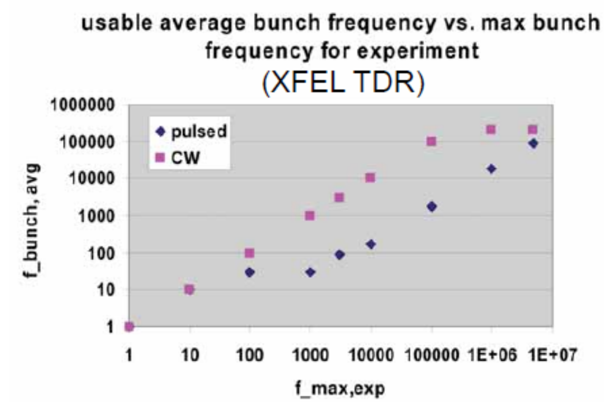
Agenda

1. *CW and LPO operation motivation,*
2. *LLRF system setup,*
3. *Module under test,*
4. *Challanges,*
5. *Moderate and high gradient operation studies,*
6. *Results,*
7. *Summary and future plans.*

Motivation for high DF studies

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





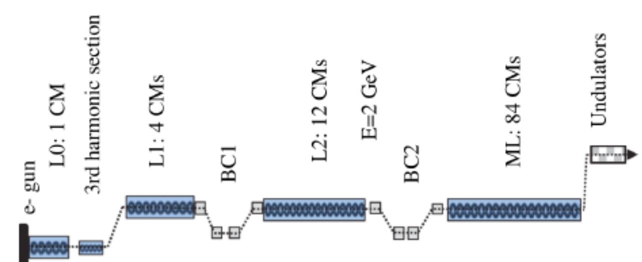
Possible costs drivers for SP -> CW:

•New (dedicated) RF gun,

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

•LLRF system adaptation,

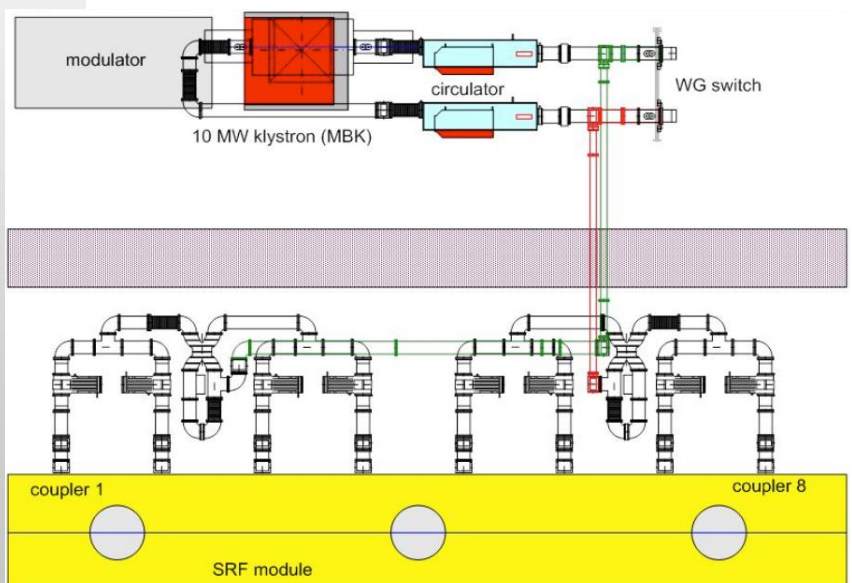
•Dedicated RF power source (for CW mode) – IOT prototype under test.



Courtesy of J. Sekutowicz

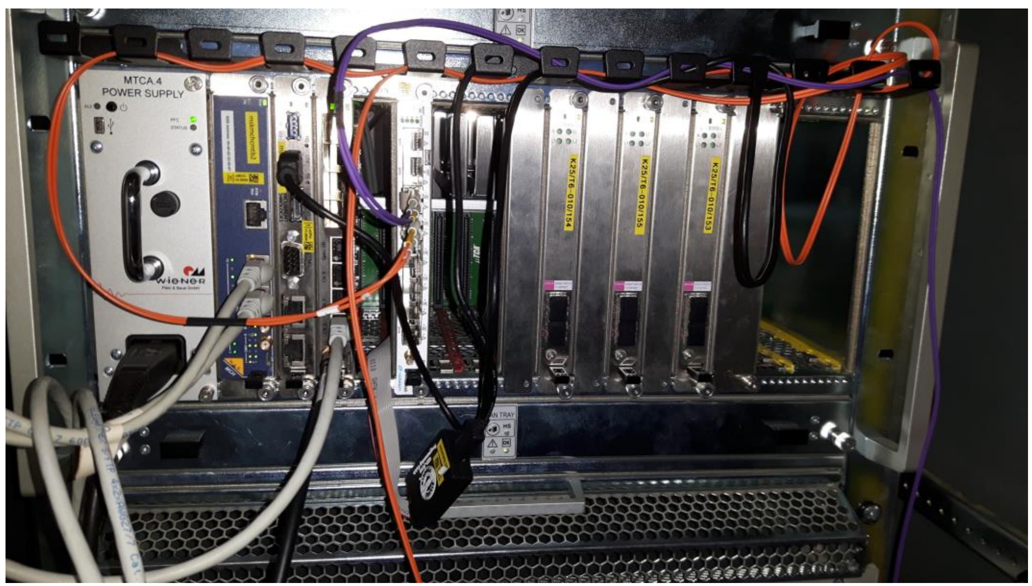
CMTB – CW/LPO teststand

- 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

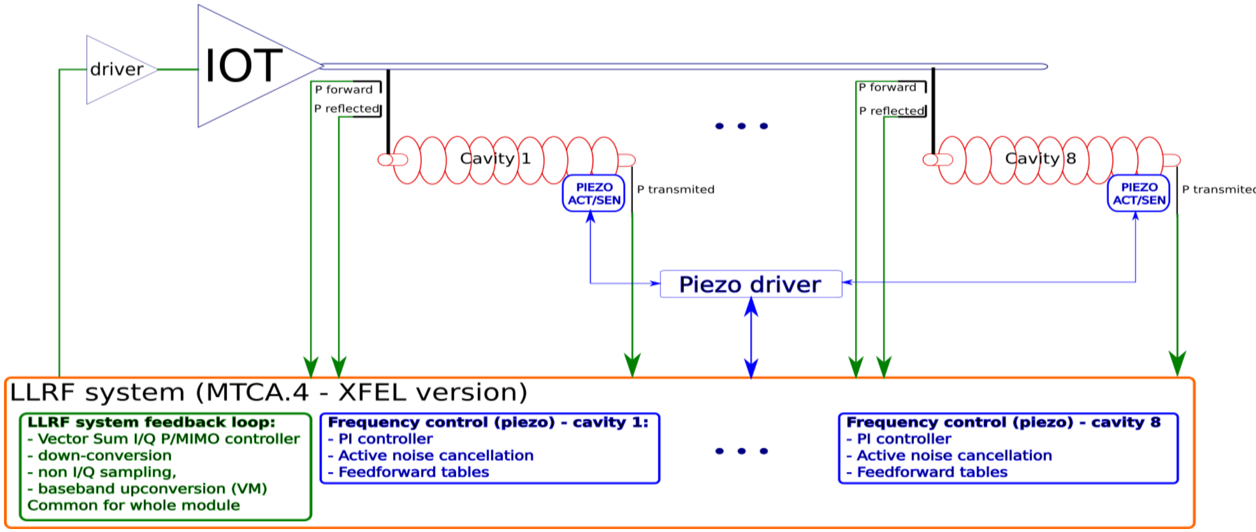


CW - LLRF system setup

- 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



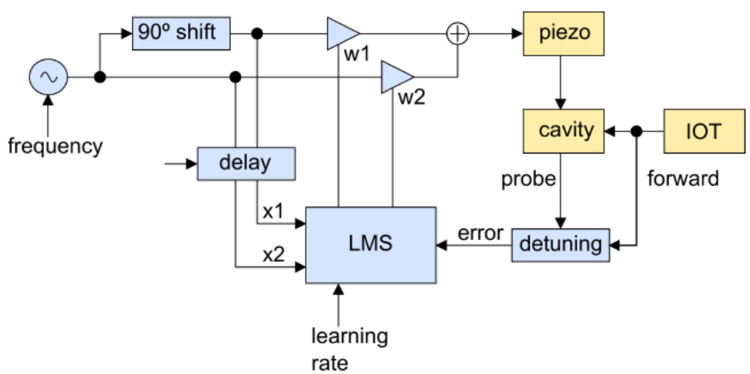
CW - LLRF system setup

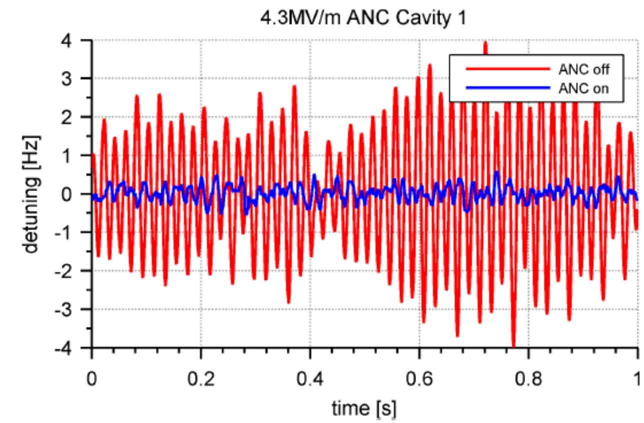


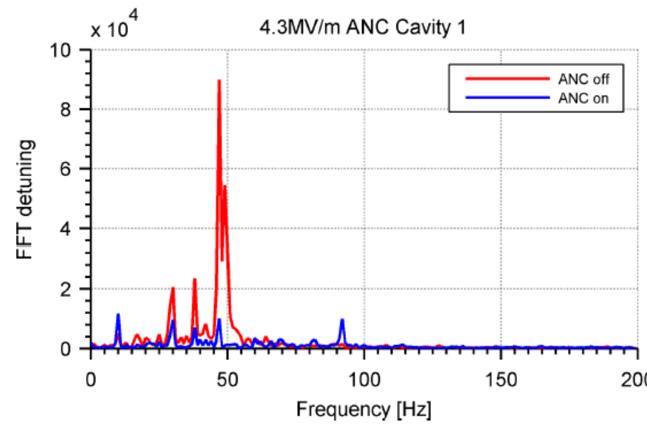
- RF field regulation loop:
  - P and MIMO controller,
  - similar to short pulse with 4,5MHz feedback sampling,
- Cavity frequency regulation:
  - DC offset,
  - PI controller (mainly I component used) for low freq (<10Hz) regulation,
  - ANC based solution for persistent microphonics effects reduction

Piezo based microphonics effect suppression

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



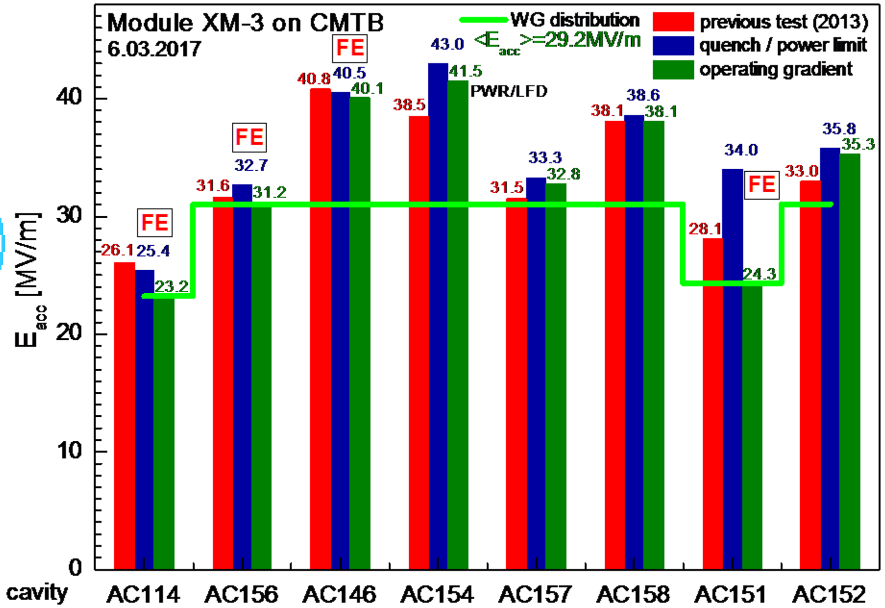




Courtesy R. Rybaniec

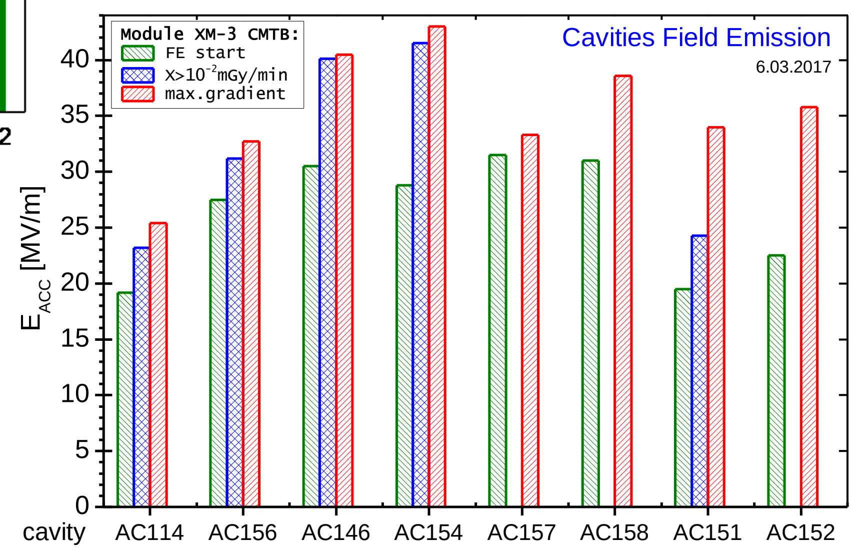
Rybaniec Radosław , Przygoda Konrad, Cichalewski Wojciech *[et all.]*: FPGA based RF and piezo controllers for SRF cavities in CW mode, w: IEEE Transactions on Nuclear Science, IEEE Nuclear and Plasma Sciences Society, vol. 64, nr 6, 2017, ss. 1382-1388, DOI:10.1109/TNS.2017.2687981

XFEL module under test



Courtesy D. Kostin

XFEL module ID: XM-3



Wojtek Cichalewski et. al,
wcichal@dmcs.pl

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.

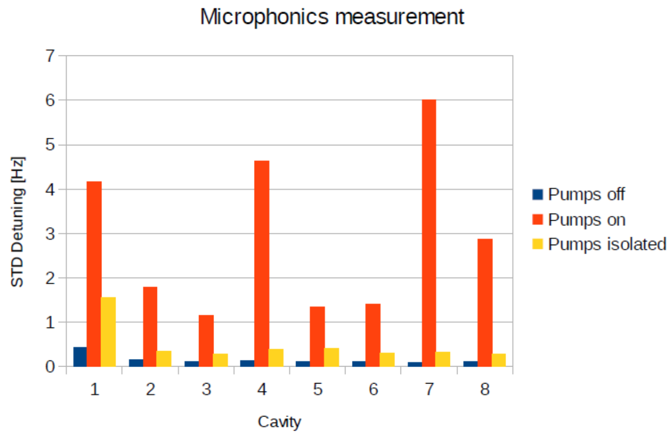
High Loaded Quality factor

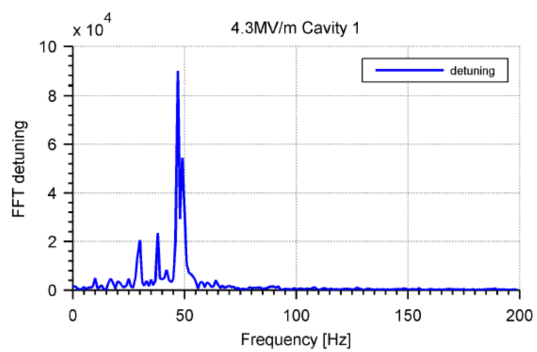
- FPC are designed to operate with input power up to 2 kW (pulse operation – range of 400kW),
- to increase Eacc for the same power – Q external needs to be adjusted,

	FLASH	XFEL	CW	CW Max ?
Ql value	3e6	4,6e6	2e7	5e7
Half BW (Hz)	216	142	32,5	13
Input power [kW] (for Eacc = 20MV/m, tuned)	32,6	21,2	5	1,95

- In order to achieve high operation gradient Q external needs to be increased high,
- 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)…..

Microphonics





Courtesy R. Rybaniec

Microphonics main sources

- Vacum pumps,
- Helium pressure fluctuation,

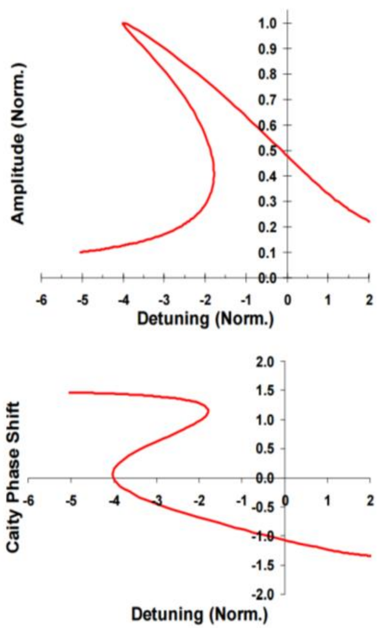
Main frequencies visible on the cavity field

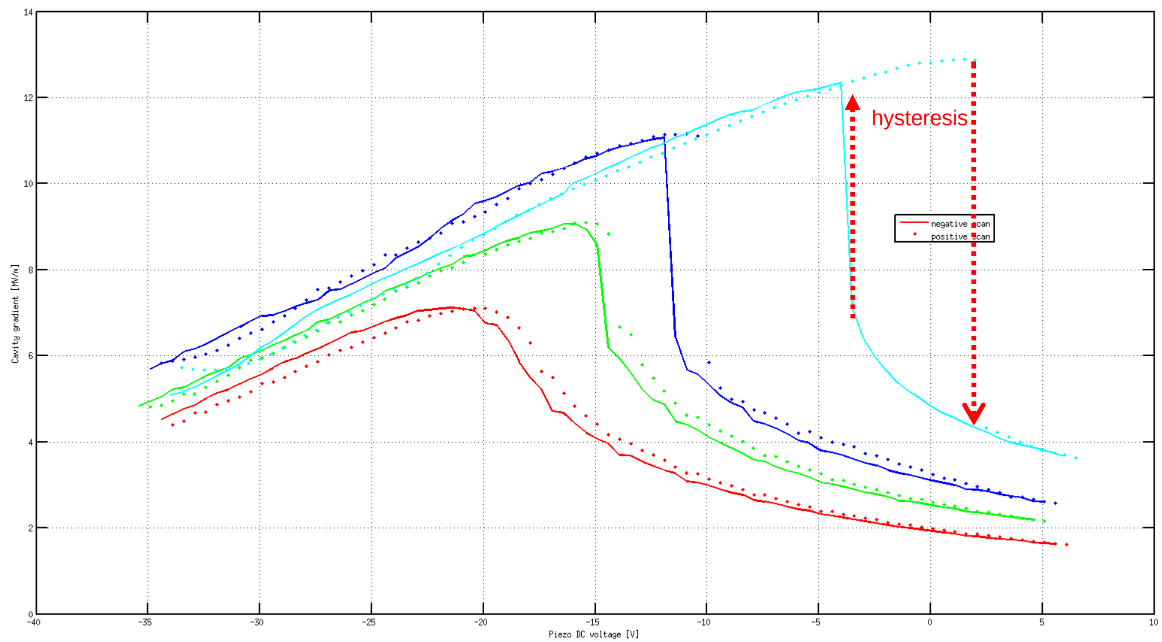
- 31 Hz
- 49 Hz

Microphonics detuning implies more RF power for compensation

Ponderomotive instabilities in VS regulation

Cavity gradient change in function of the detuning shows hysteresis effect



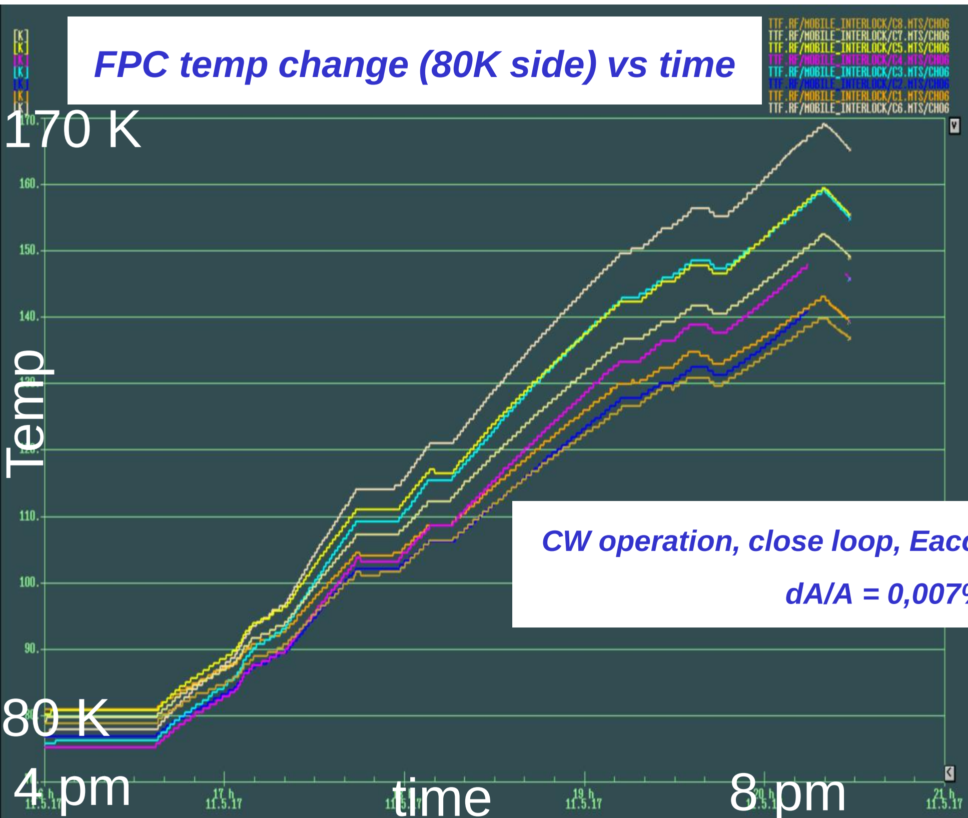


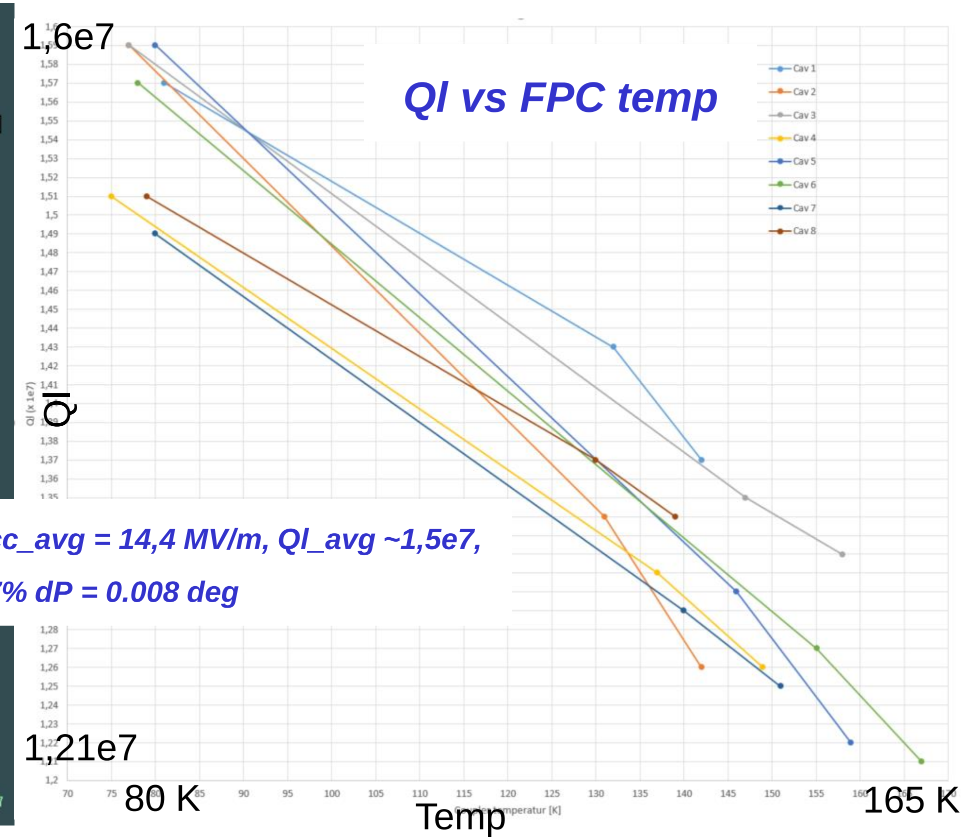
Cav amplitude in function of detuning (measured for different input power SP)

- 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.



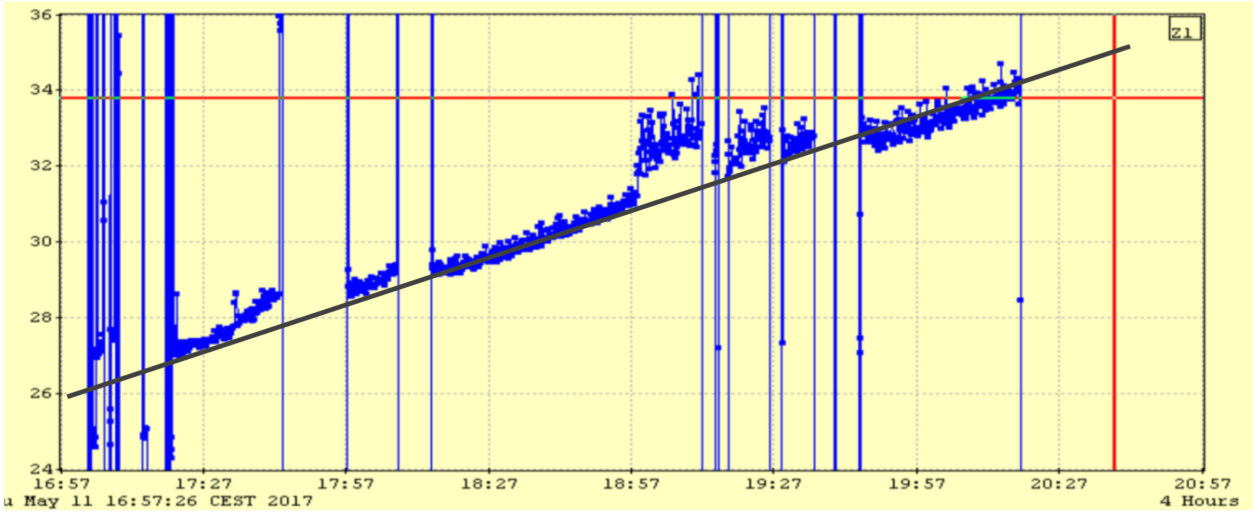


CW operation, close loop, Eacc_avg = 14,4 MV/m, Ql_avg ~1,5e7,

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

- The increase of the IOT power results also in the phase shift (due to nonlinearity) this can impact the detuning estimation and then piezo feedbacks,
- Even tough the conditions are changing the VS regulation is better than XFEL spec.

IOT nonlinearities

IOT prototype (by CPI) is being used for cavities supply during CW/LPO study.

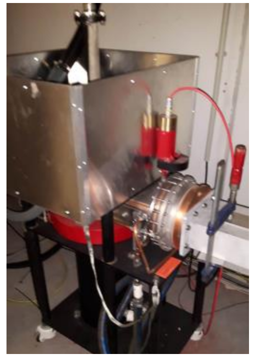
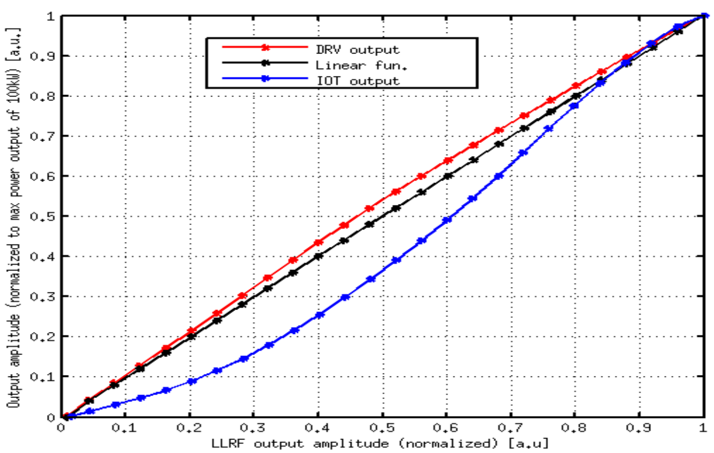
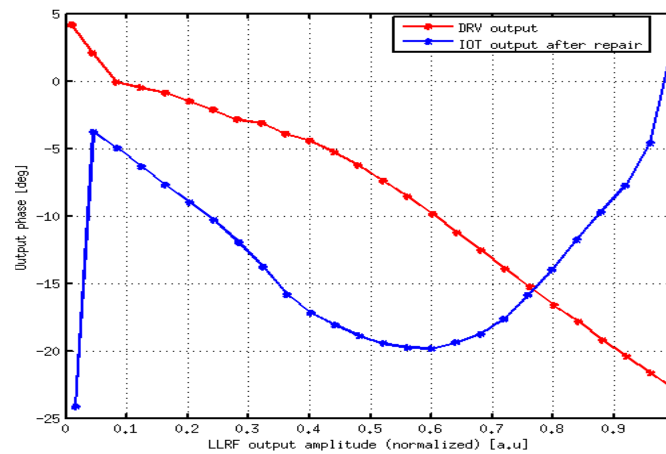


TABLE III. Parameters of IOT prototypes.

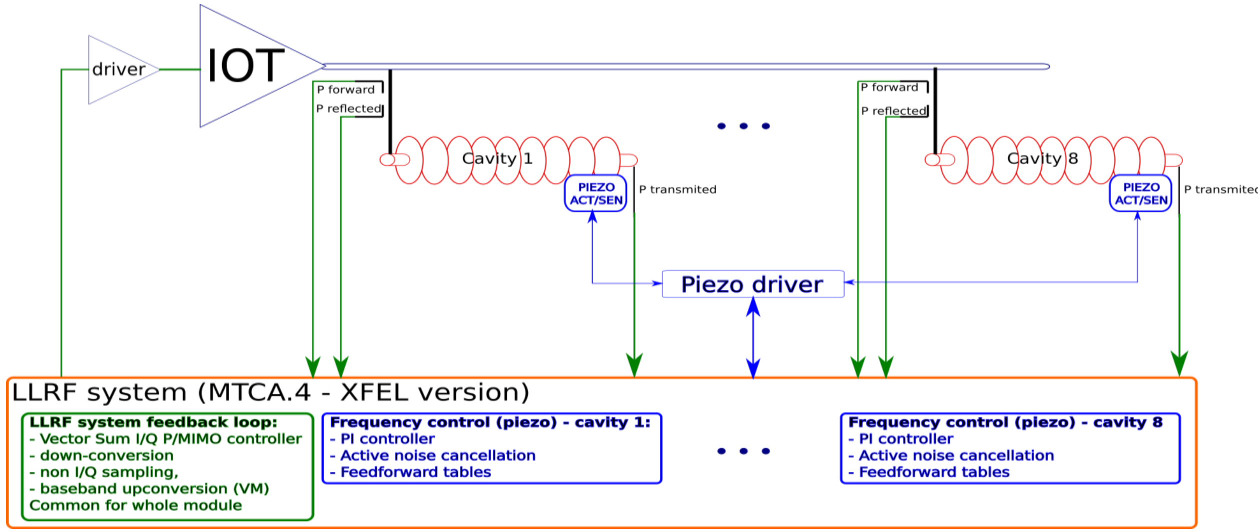
	Unit	Specification	Prototype I 2009	Prototype II 2013
F	[MHz]	1300	1300	1300
cw P_{out}	[kW]	120	85	105
Gain	[dB]	>22	22.3	22.7
Efficiency	[%]	>60	54	63
V_{beam}	[kV]	47–49	47–49	47–49





- Gain increase can cause sudden IOT ouput power jump during close to open loop transition,
- Phase shift at the output of the IOT can influence cavity detuning estimation -> limit performance of the piezo feedbacks.

CW - LLRF system setup



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

QI ~1,5e7 operation

Close loop CW operation:

-Proportional RF feedback,

-Piezo I controller

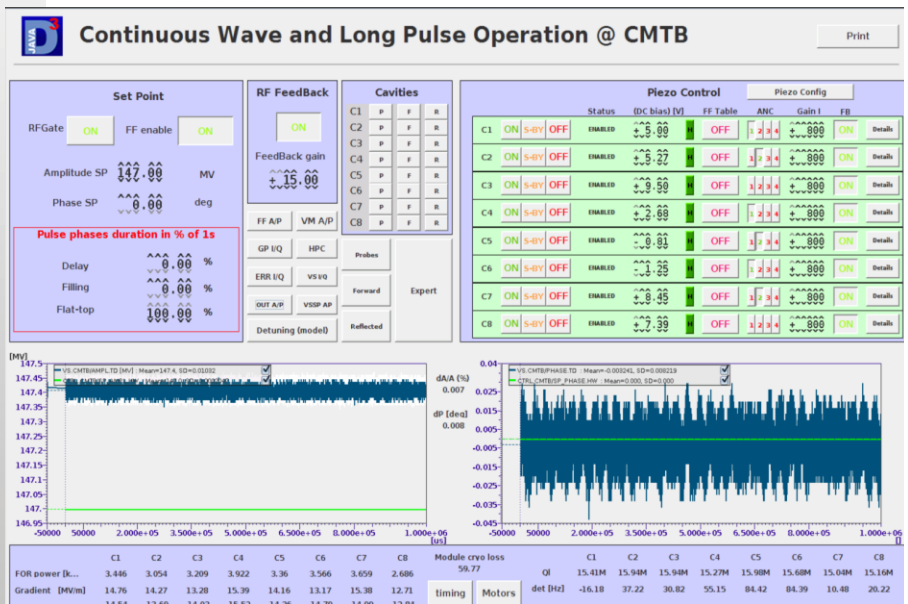
-ANC filters for some resonators (mainly 31Hz & 49 Hz),

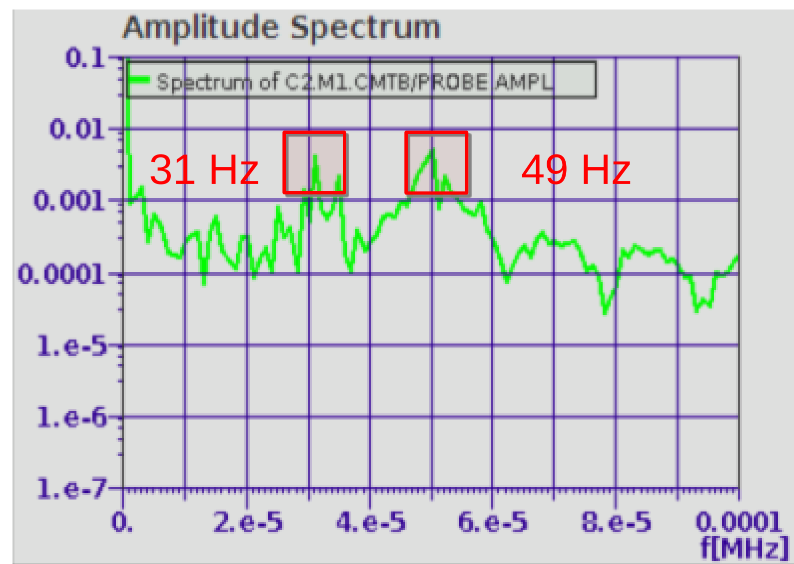
-„cold couplers" QI readout:

	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)

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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Wojtek Cichalewski et. al,
wcichal@dmcs.pl

LLRF2017
Low Level Radio Frequency Workshop
BARCELONA
16-19 October
2017
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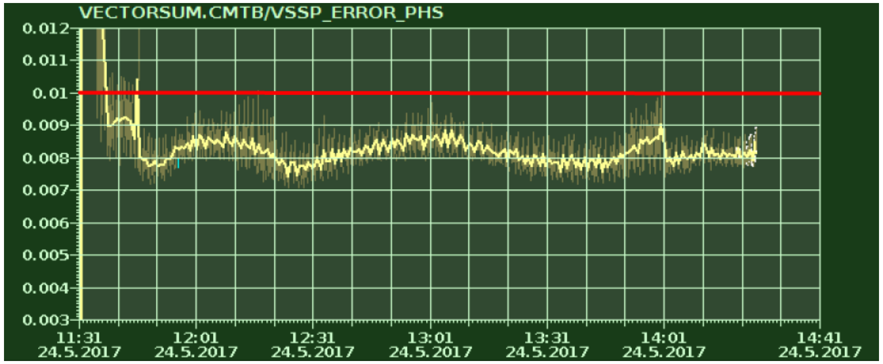
Results medium gradient ~15MV/m

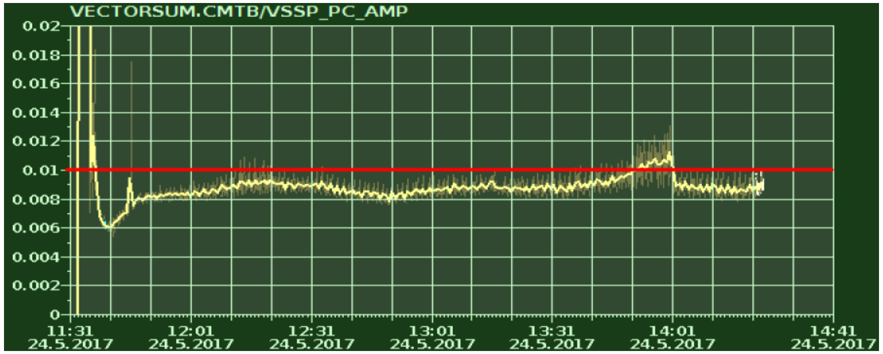
Configuration:
-Proportional RF feedback,
-Piezo I controller
-ANC filters for some resonators

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

Cav	Eacc [MV/m]
1	17,80
2	14,39
3	14,07
4	16,08
5	14,35
6	13,03
7	14,92
8	12,76



Amplitude stability during studies



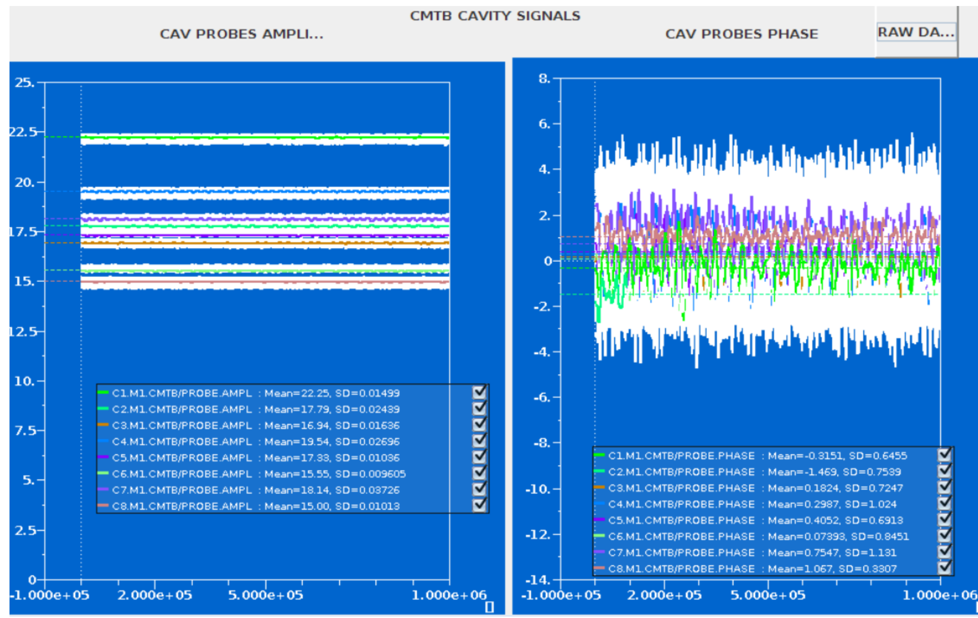
Phase stability during studies

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

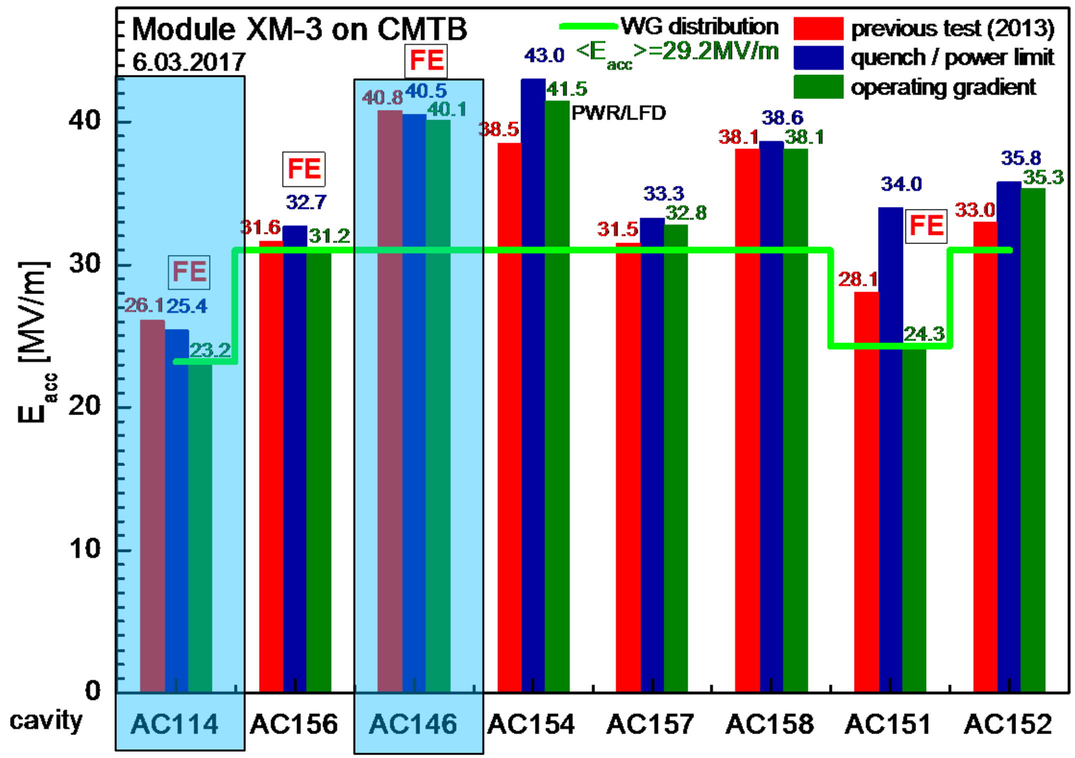


- *Individual cavities performance exceeds field regulation thresholds,*
- *VS controll does not focus on the individual cavity regulation*

Single cavity operation

- VS is not optimal for single cavity control,
- Try to operate single cavity to verify the regulation performance

Cav	Ql	Pfwd [W]
1	2,80E+07	8,72E+02
2	1,95E+07	1,25E+03
3	2,16E+07	1,13E+03
4	2,00E+07	1,22E+03
5	1,90E+07	1,28E+03
6	1,80E+07	1,36E+03
7	1,70E+07	1,44E+03
8	1,78E+07	1,37E+03



Cavity 1 and cavity 3 have been chosen – highest Ql (lowest input power needed)

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

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:

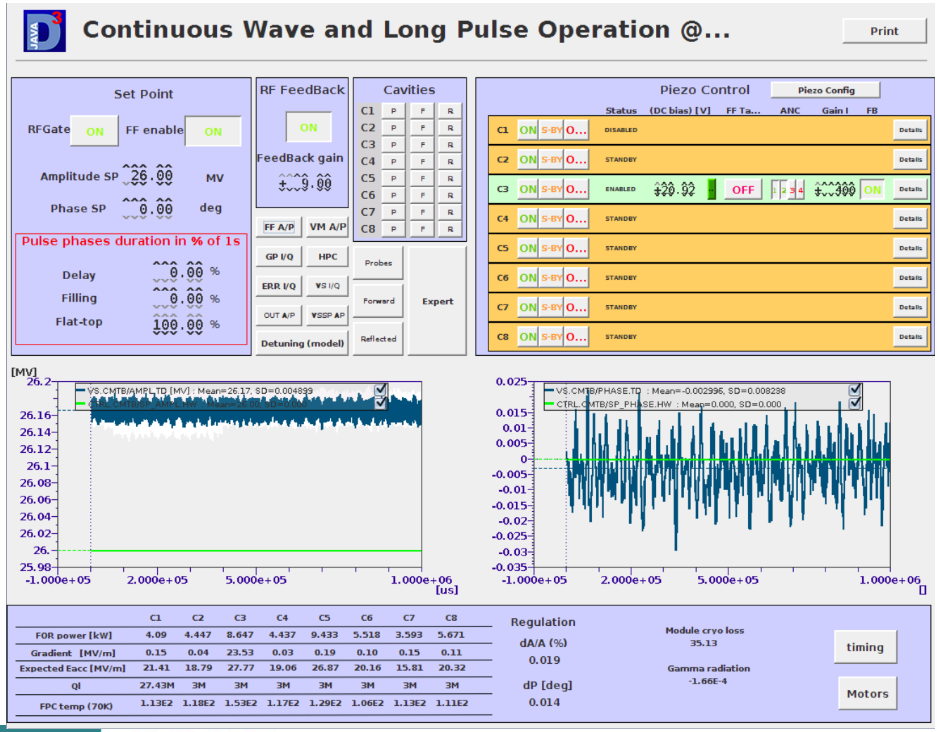
dA/A = 0.018%   dP = 0.016 deg

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),
- power distribution for the single cavity operation can/should be optimized,



Summary and future plans

1. CW operation in close loop is possible with current setup with grad up to 18 MV/m (average),
2. Module operation for average grad of 15 MV/m with fulfilled XFEL specs.,
3. Higher cavities Ql will reduce required input power and it is still not a challenge for precise field regulation.

Future plans

1. QI increase by modifying fundamental power couplers – planned late 2017,
2. Possible QI range – up to 5e7,
3. Long Pulse operation study,
4. Optimization of the cavity in resonance filling (for LPO)
5. Max Eacc / max DF study.

Wojtek Cichalewski et. al,
wcichal@dmcs.pl

Thank You