Experiences from Tesla cavities module operation in CW and Long Pulse modes at CMTB

W.Cichalewski, J.Branlard, W.Jalmuzna, A.Piotrowski, K.Przygoda, J.Szewinski, J.Sekutowicz

Experiences from Tesla cavities module operation in CW and Long Pulse modes at CMTB

4th RF-tech Workshop Annecy, 25.03.2013

HELMHOLTZ | ASSOCIATION

DESY

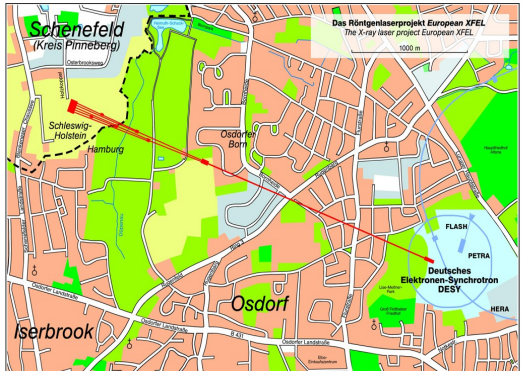
Overview

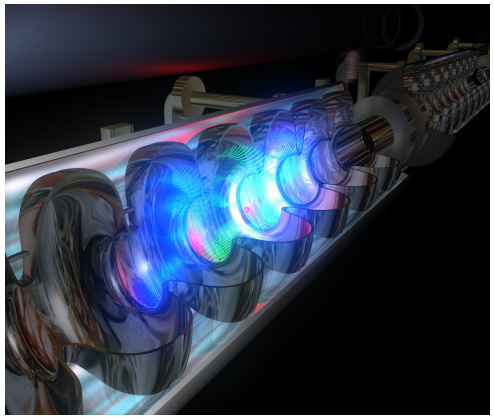
- Intro
  - Pulsed systems
  - Motivations for CW
  - Challenges
- Tests setup
  - HP hardware
  - LLRF hardware – UTCA
  - firmware/software algorithms
- Results
  - Continuous Wave
  - Long Pulse
- Outlook and future work

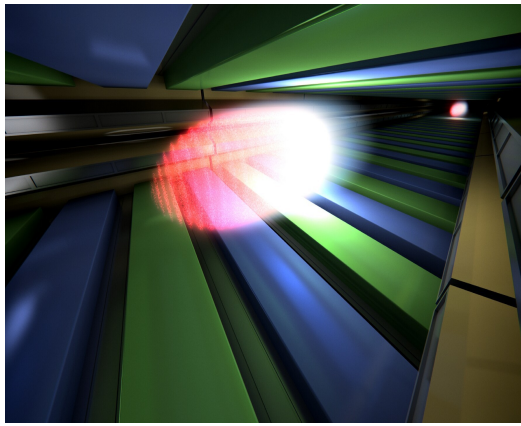
Introduction – pulsed system

European Xray Free Electron Laser

- Total Length – 3.4 km
- Depth of tunnels – 6-38 m
- Cost ~1.15 bilion Euro
- Consists of superconducting linear acc.
- Accelerator length – 1.7 km
- Number of modules – 101
- Laser wavelength – 0.05-6 nm
- Max. bunch per second – 27k
- Peek brilliance – 5*10^33
- Average brilliance – 1,6*10^25



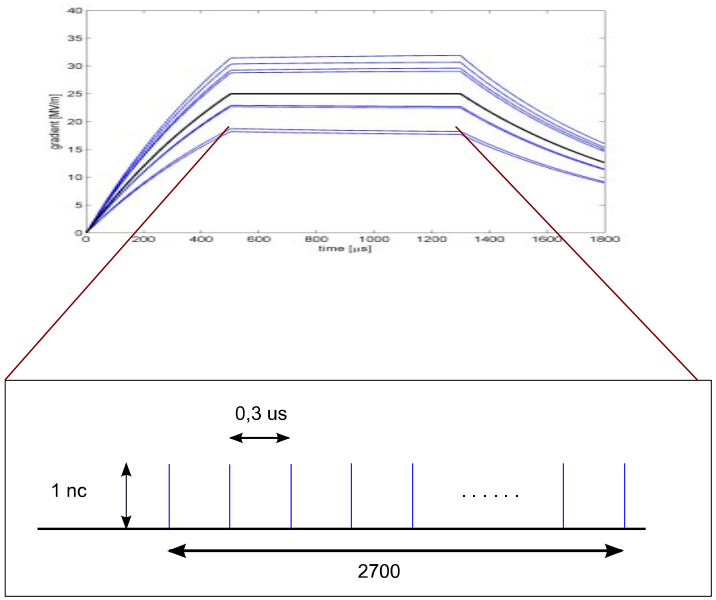




Introduction – pulsed system

XFEL facts :

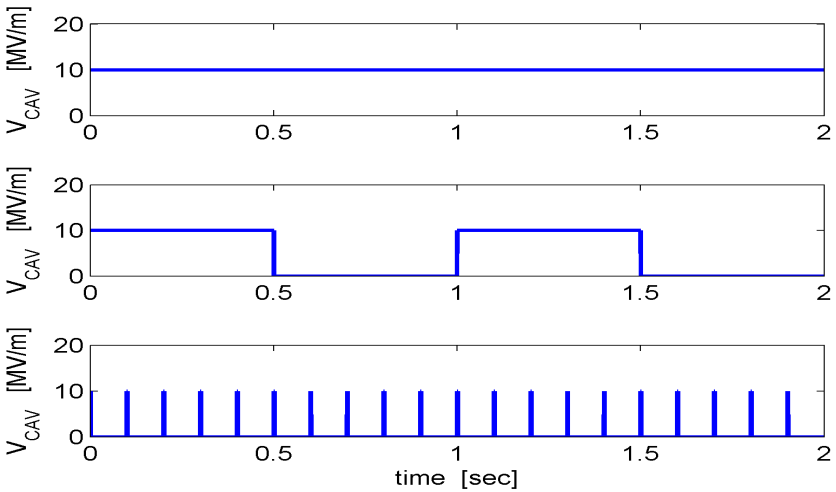
Nominal Energy	GeV	14.5 → 17.5
Beam pulse length	ms	0.60
Repetition rate	Hz	10
Max. # of bunches per pulse		2700
Min. bunch spacing	ns	200
Bunch charge	nC	1
Bunch length, σz	μm	< 30
Emittance (slice) at undulator	μm*rad	< 1.4
Energy spread (slice) at undulator	MeV	1



Introduction - motivation for CW

> X-FEL beam parameters can be even more attractive

- Flexibility in bunch patterns shaping,
- Higher efficiency → much more photon bursts per second (from 10b/s to eq. ~90 b/s @ 1kHz rep rate),
- Relaxing bunch-bunch distance to some u-seconds → less technical demanding detectors,
- Increasing photon burst repetition rate (few kHz) → less expensive lasers can be used.



Introduction – challenges

- The superconducting cavities are/can be operate in CW mode but current accelerator systems parameters are not fully suitable for Long Pulse / Continuous Wave operation,

- Changes are required for:
  - Cryogenic plant,
  - Superconducting RF gun,
  - RF High Power delivery,
  - LLRF control system.

Introduction – challenges – cryogenic plant

- Dynamic heat losses are caused by cavities walls heating (by RF power),
- Operating temperature reduction can benefit in cavity gradient increase for the same losses level (eq. ~40% higher gradient for 1.8 K instead of 2 K operation)
- With **assumption** of heat load limit of **20W/module**

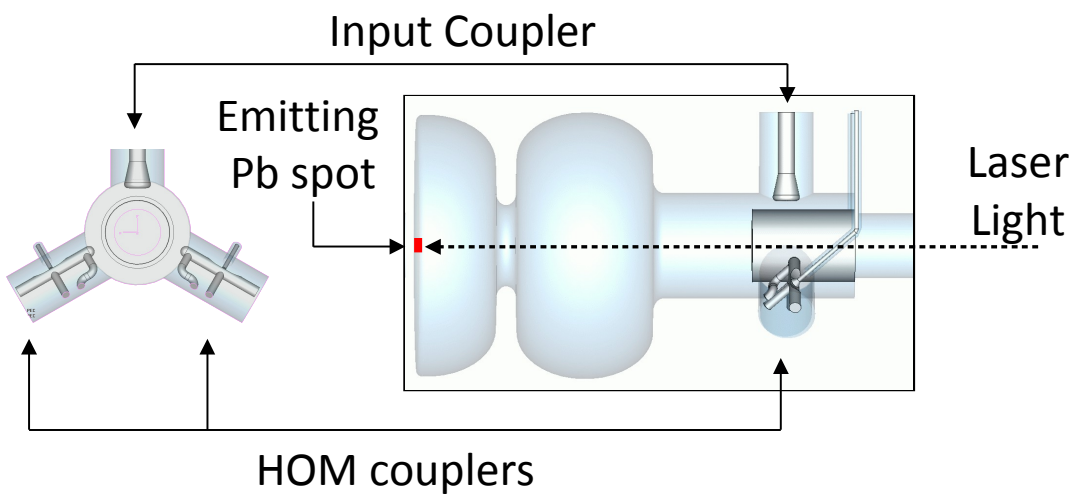
	Short-pulse operation (2K)		Near-cw operation (1.8K)	
T range	Capacity (116 CM) [W]	Heat Load (83 CM) [W]	Capacity (83 CM) [W]	Heat Load (83 CM) [W]
2 K (1.8)	**2450**	1204	**3137**	2091
5-8 K	4000	2880	5120	3413
40-80 K	30000	12556	38440	25625

Estimation by B. Petersen

→ means for 1.8K operation around 30% higher system capacity is required.

Introduction – challenges – SRF GUN

HZB (BESSY), JLab, INS, Max Born and DESY are involved in the RF gun preparation.



Wavelength	QE
213 nm	2.7E-03
258 nm	4.8E-04

Parameter	Unit	Value
Spot radius	[mm]	1.5
Nominal *Ecath* at cathode	[MV/m]	~50
Emittance (slice) for 1 nC	µmrad	< 1.4

Laser parameters for 55000 bunches (1 nC)

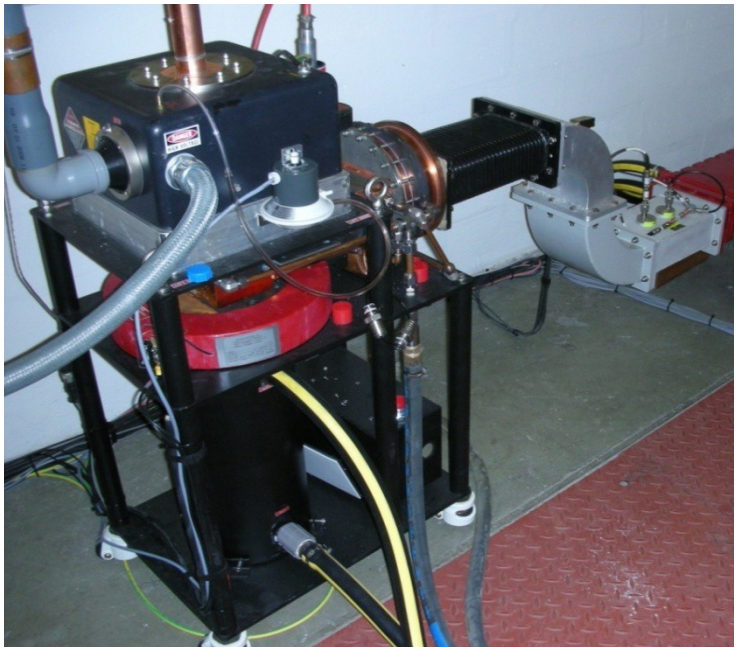
Wavelength	Pulse energy [µJ]	Power [W]
213 nm	2.1	0.12
258 nm	10.0	0.55

Courtesy J.Sekutowicz DESY

Introduction – challenges – RF high power

- Current 10MW klystrons not suitable for CW and LP operation – nominal pulse length ~1,6 ms
- IOT has been designed and tested to provide LP and CW operation possibility

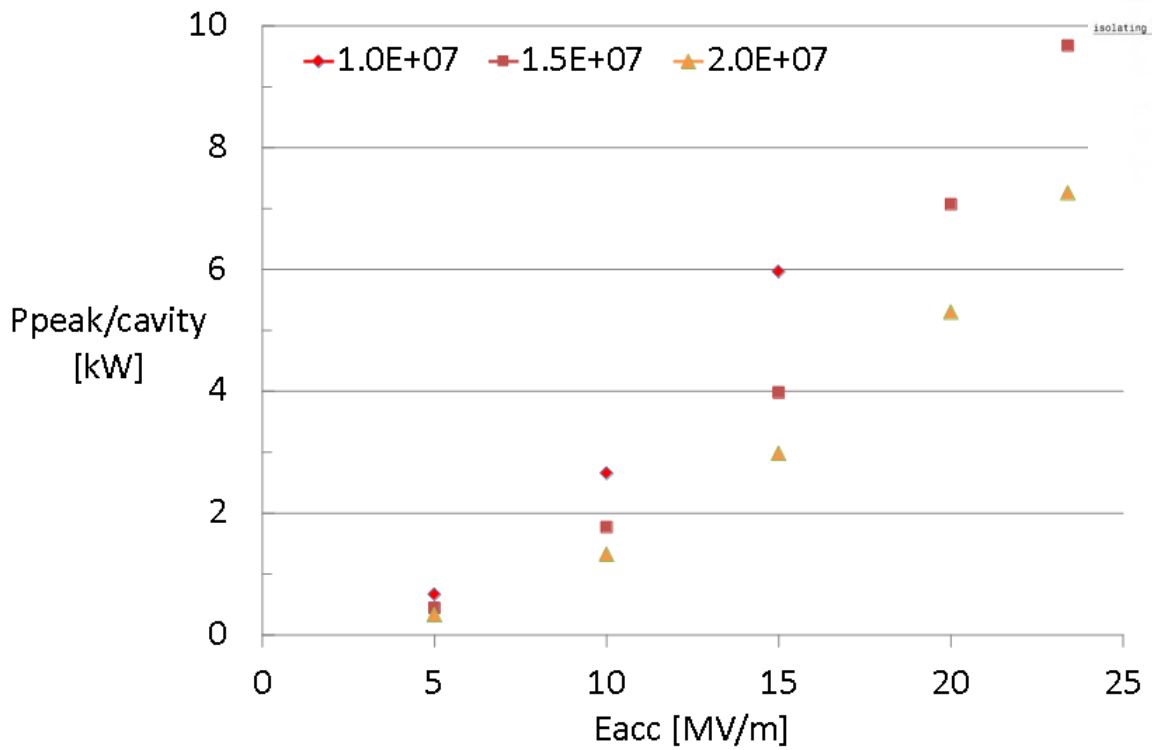
Parameter	Unit	Spec	Measured at CPI and (DESY)
F	[MHz]	1300	1300
Output P	[kW]	60-120	85 (80)
Gain	[dB]	>21	22.3
Efficiency	[%]	>60	54
Voltage	[kV]	36-50	45-48

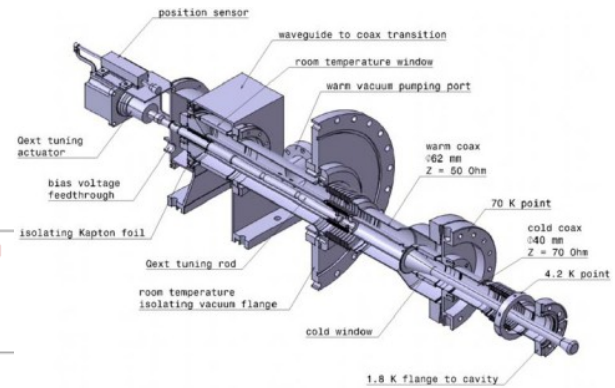


- Prototype device (by CPI) has been used during CMTB tests

Introduction – challenges – control loop performance

- The two assumptions – derived from system limitations:
  - Maximum cryogenic heat load **<20W**
  - Maximum average power per cavity input coupler **<1.45 kW** (design limitation)

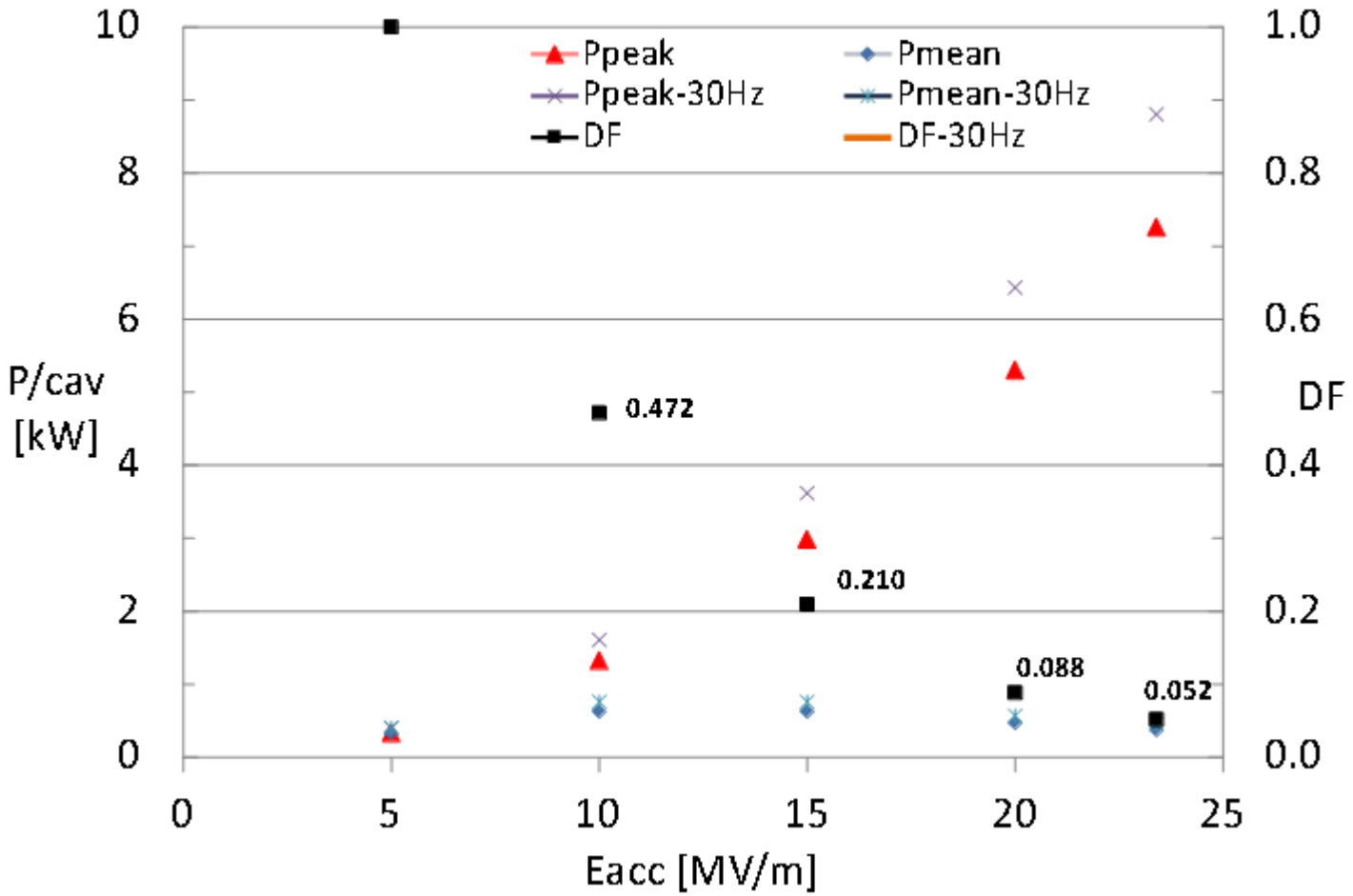




- Loaded Quality factor optimization for **increasing** field **gradient** for lower input power ~2*10e7 (for assumption of 14.5 GeV beam energy)

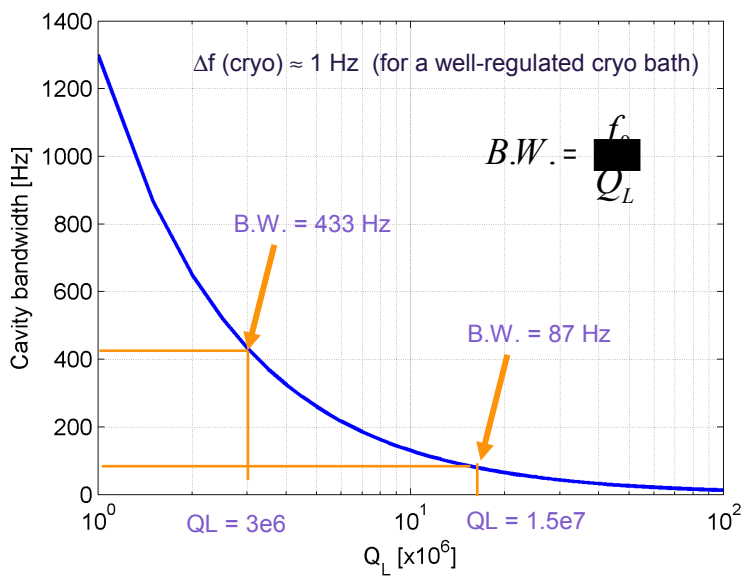
Introduction – challenges – control loop performance

> Operation duty factor (DF) limitation has to be introduced in order to satisfy mean input coupler power limitation

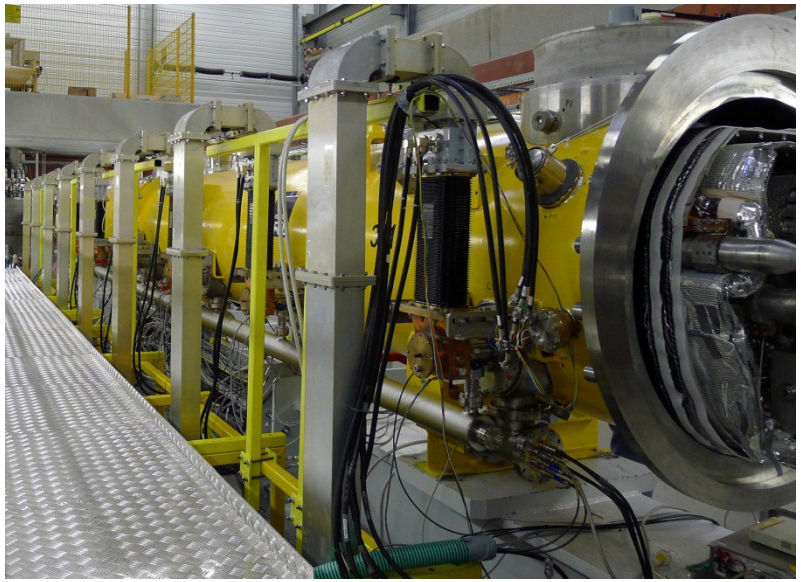


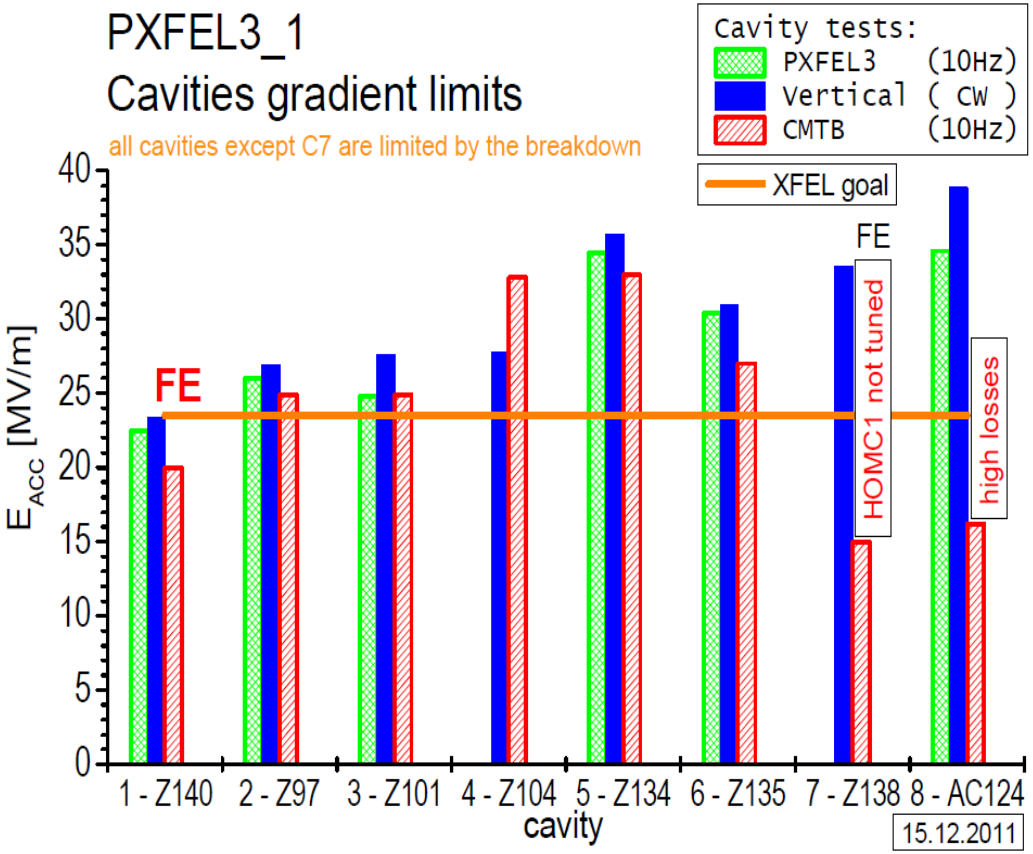
Introduction – challenges – control loop performance

- LLRF system has been originally design for short pulse operation:
  - control algorithms (PID, MIMO controllers, learning Feed Forward, etc.),
  - cavity parameters identification (Ql, detuning, etc),
  - data acquisition and data analysis methods.
- Cavity parameters for CW → gradient up to 13 MV/m and Ql = 2e7
  - Gradient level is considered as a moderate,
  - High loaded quality factor implies lower cavity bandwidth → more effective control over the microphonics influence is a must.



Test setup – CryoModule Test Bench





- PFWD equally distributed
- All cavities on resonance
- QL = 1.5 * 10^7

Test setup – HP system

Klystron

THALES 1.3 GHz 10MW klystron

- Power
  - Klystrons: MW pulsed
  - IOTs: kW CW
- Efficiency
  - Klystron < IOT
- Cost
  - Klystron > IOT
- Lifetime
  - Klystron < IOT
- Sensitivity to HV fluctuations
  - Klystron > IOT

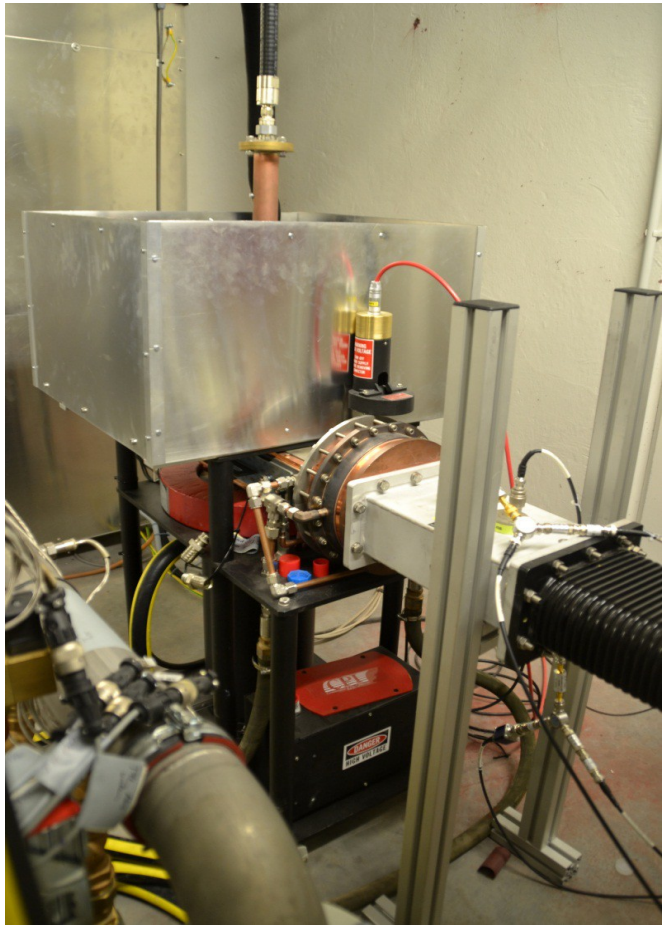
Inductive Output Tube (IOT)

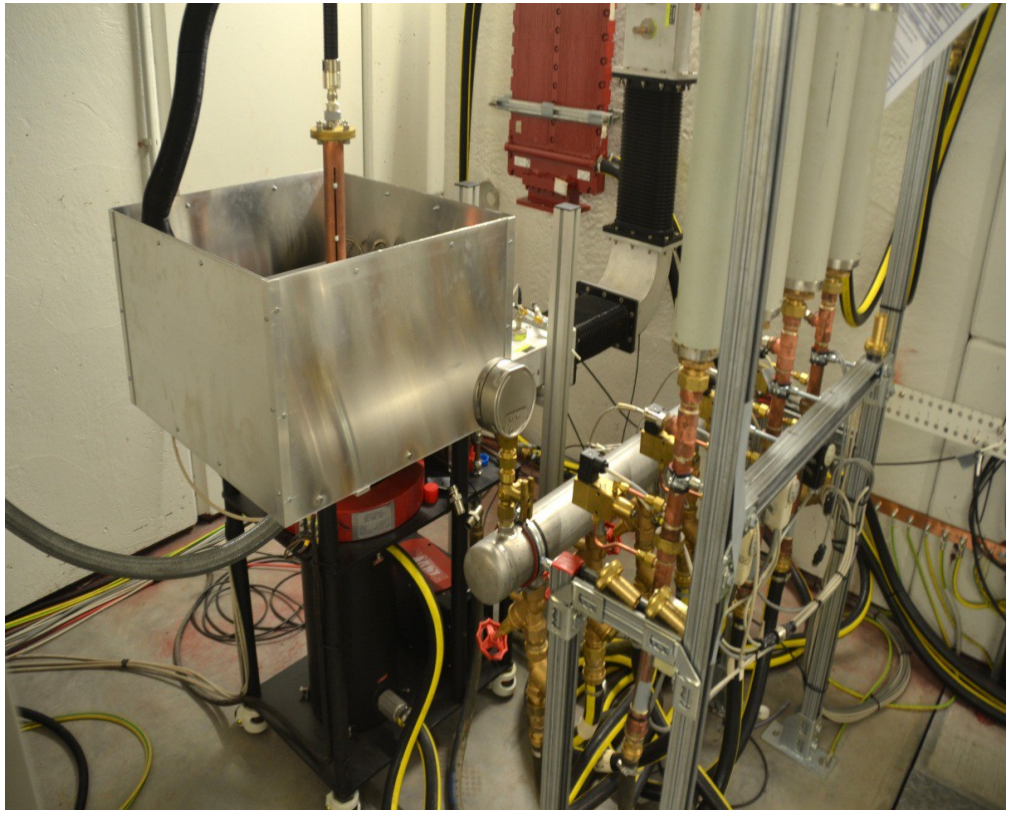
CPI 1.3 GHz 20 kW IOT

Reference: “Comparison of Klystron and Inductive Output Tube (IOT) Vacuum-Electron Devices for RF Amplifier Service in Free-Electron Laser”, A.Zolghari *et. al.* EPAC 2004

Test setup – HP system

> IOT has been installed in the CMTB hall and tested for output power up to 20 kW.





Test Setup – UTCA system

CRYOMODULE

1 2 3 4 5 6 7 8

FWD REF PRB PZT

IOT

MO + REF

RF

LOGM

PREF PFWD PRB

8

PZT 16

PZ16

PS

uTCA crate

RTM

AMC

VM

RF

LO

CLK

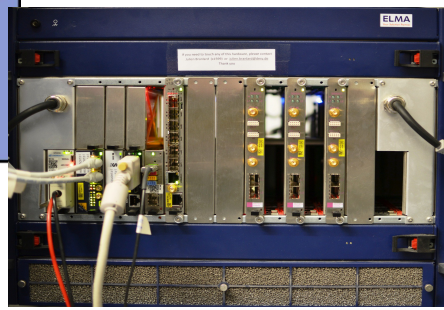
DWC

Backplane

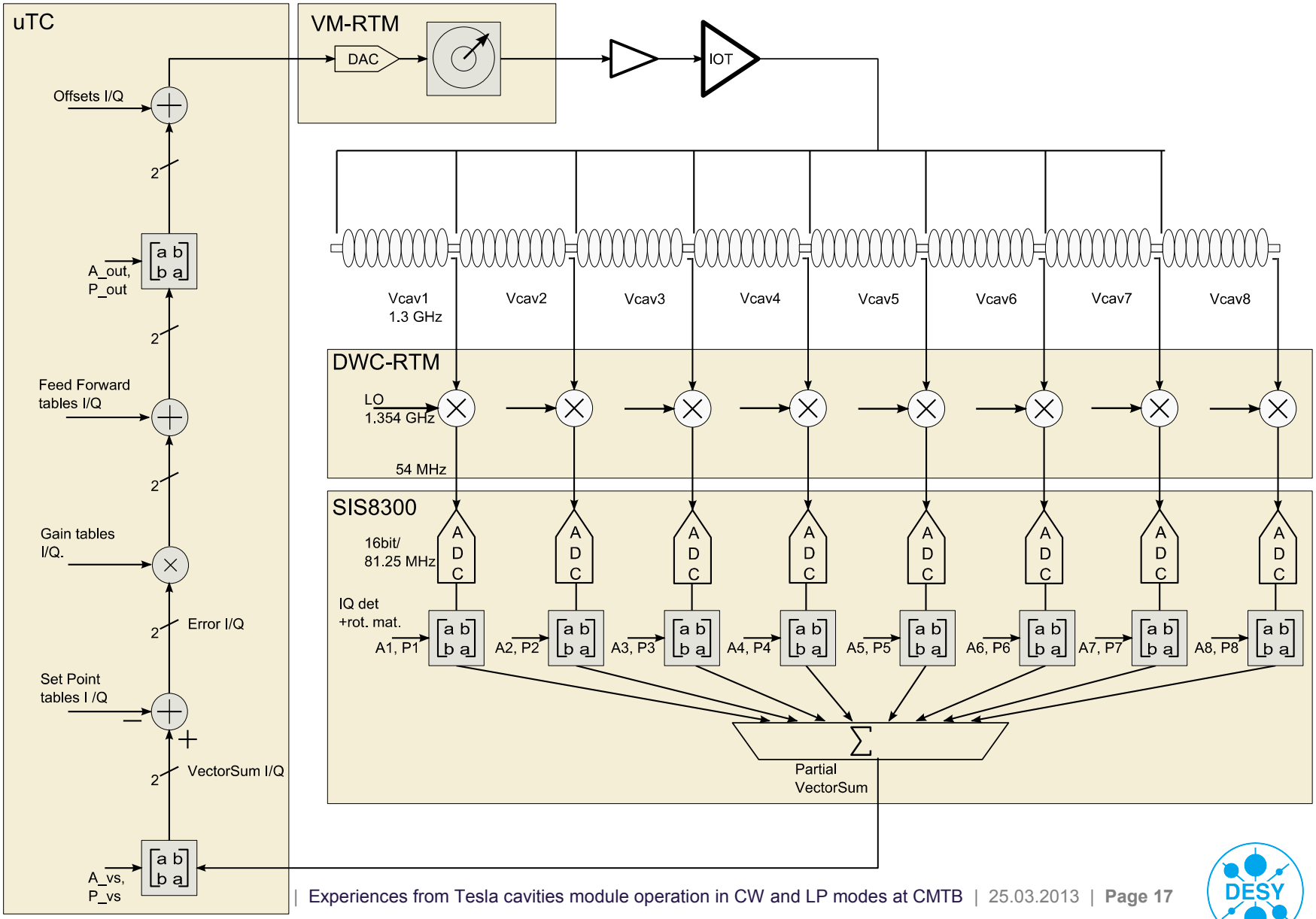
uTC

SIS

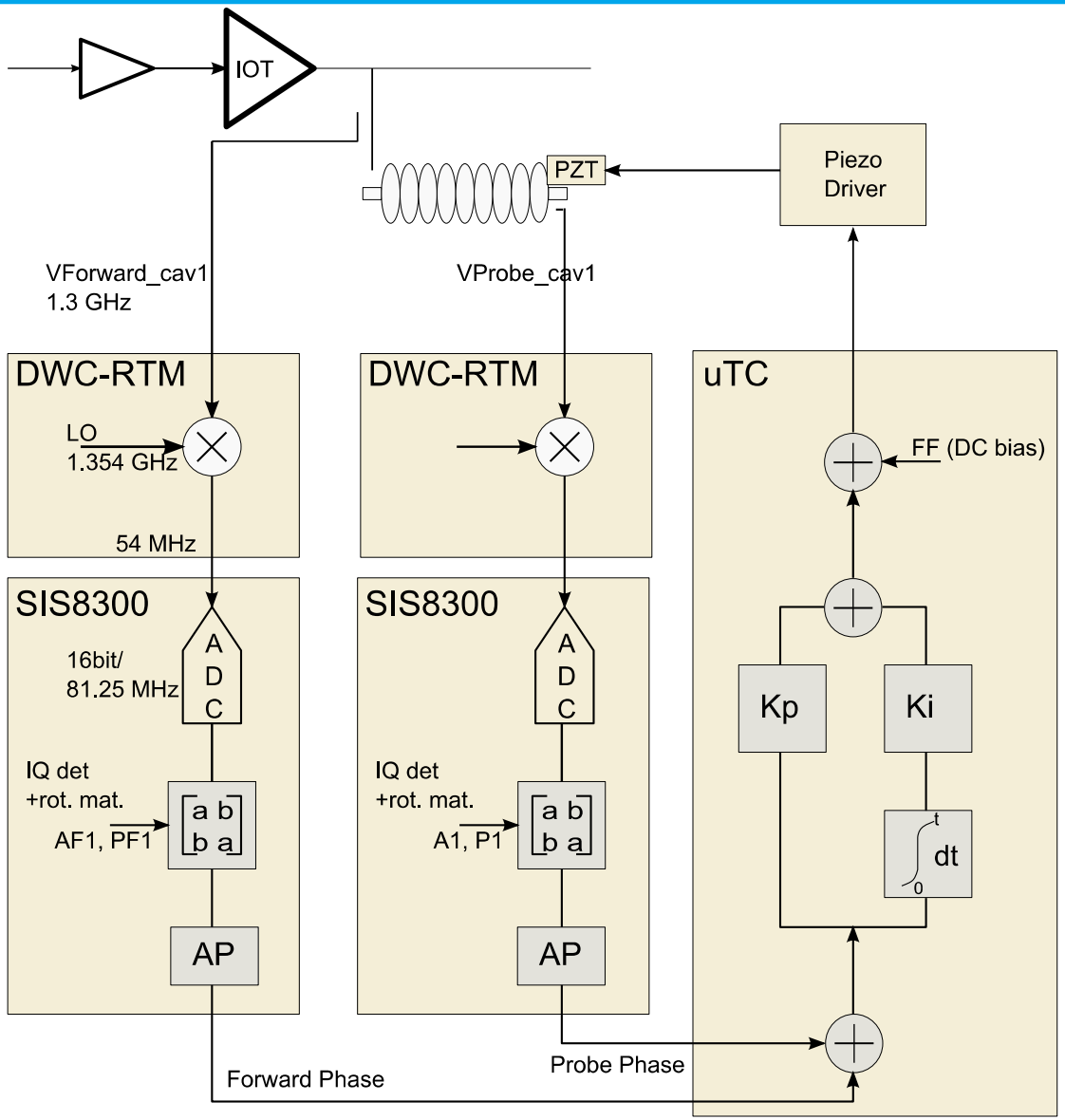
ADC + Calib + part. VS



Test Setup – LLRF controller configuration



Test Setup – Cavity fine tuning piezo feedback

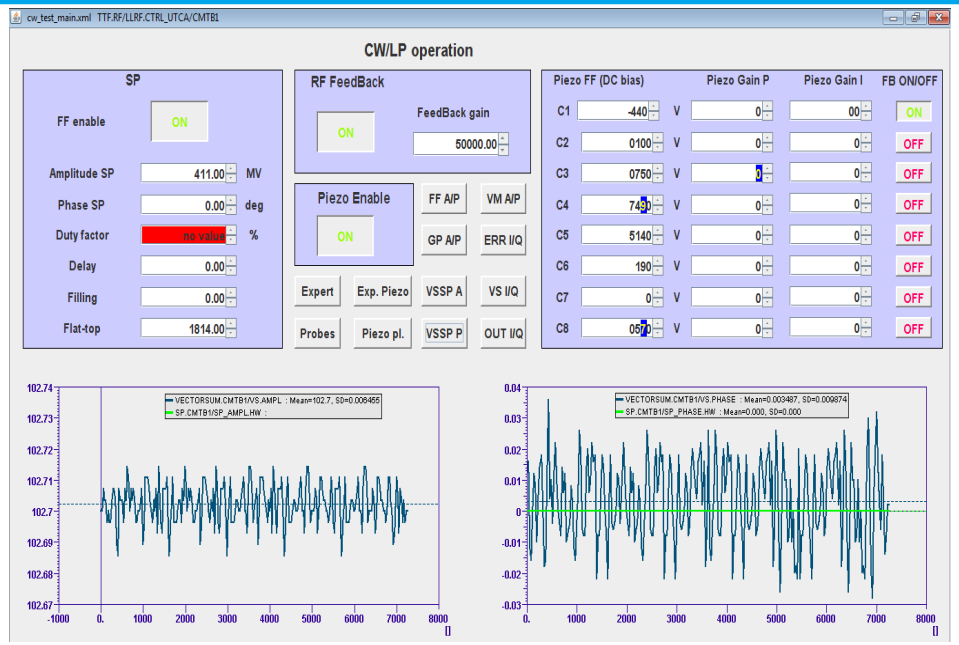


Test setup – firmware and software modifications

- Firmware modifications:
  - Controller works with full speed (81.25 MHz),
  - Control tables size has not been changed (16k samples),
  - Samples spacing has been increased (to cover 1s operation),
  - Data acquisition for CW operation was at the level of 65kHz for 1s long waveforms (higher resolution - up to 9MHz data acquisition possible for defined timing window),
  - Cavities forward and probe signals phase transmission to uTC,
  - PI controller realization for Piezo

- Front-end server and tools modifications:
  - Functionality extension for piezo feedback management,
  - Different data buffer acquisition and visualization

Results – Continuous Wave



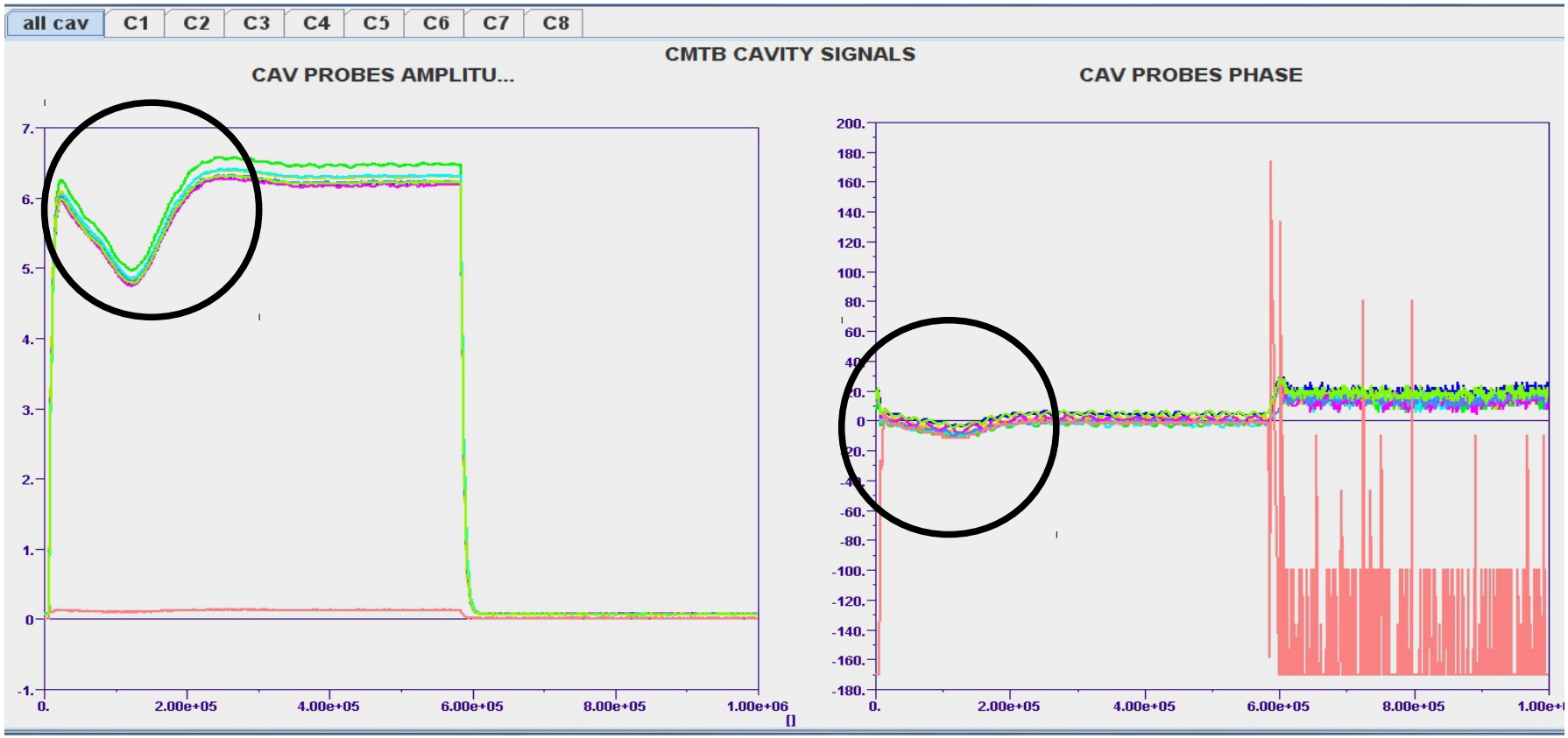
Operations at 3MV/m
- 8 cavities at 3MV/m
- Problem with HOM cav 7 → detune

Operations at 5MV/m
- 7 cavities at 5MV/m
  (~ 1 kW from IOT)
- Cryo losses ~ 2.5 W
- LLRF FB
- Cavity tuning using slow tuner + piezo static tuning
- Stable operations over 20 hrs (on resonance)

In-loop Regulation performance
- Amplitude: **$\Delta A/A$ = 6x10-5 (RMS)**
- Phase: **$\Delta\phi$ = 0.0098° (RMS)**

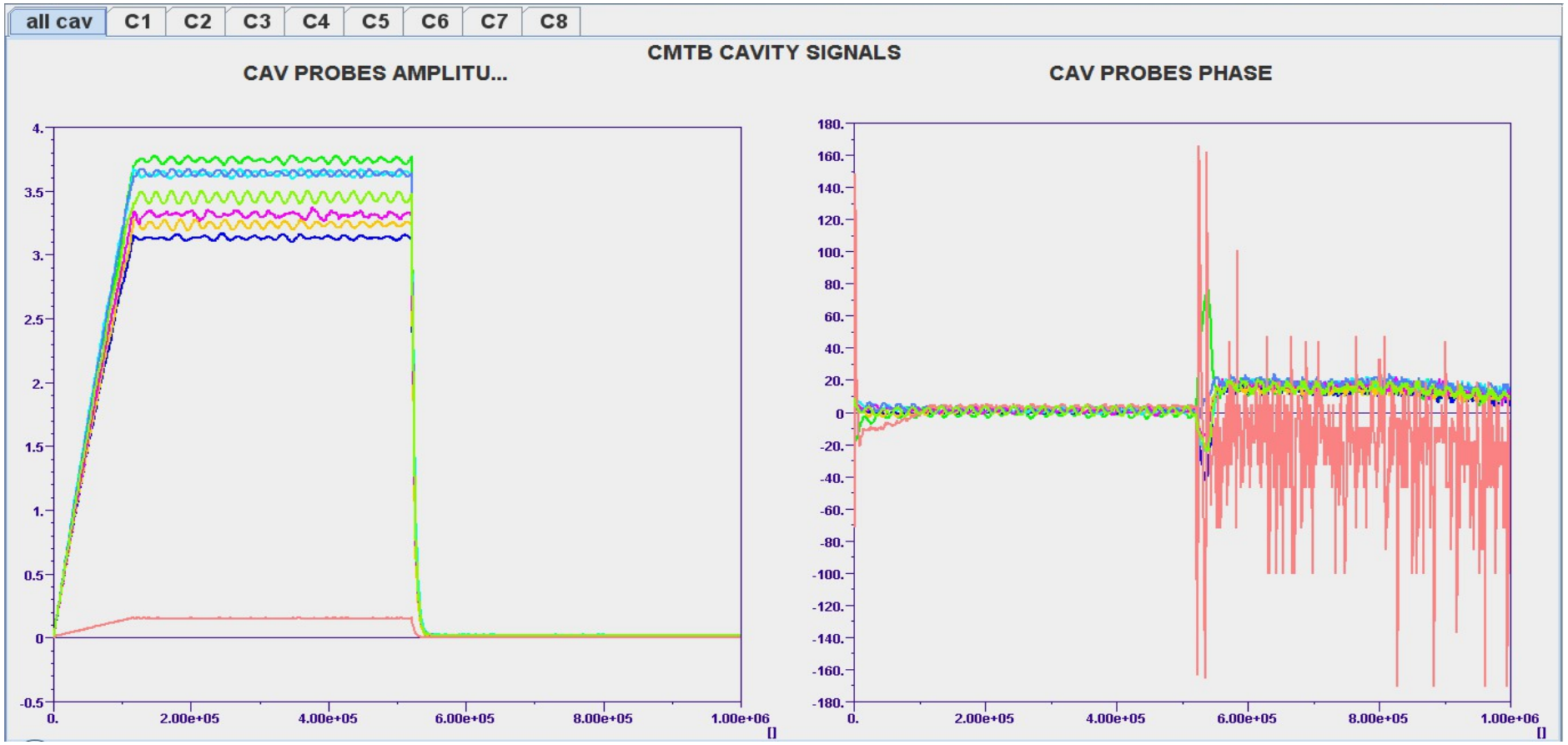
Results – long pulse operation

> IOT prototype HV rise transient:



Results – long pulse operation

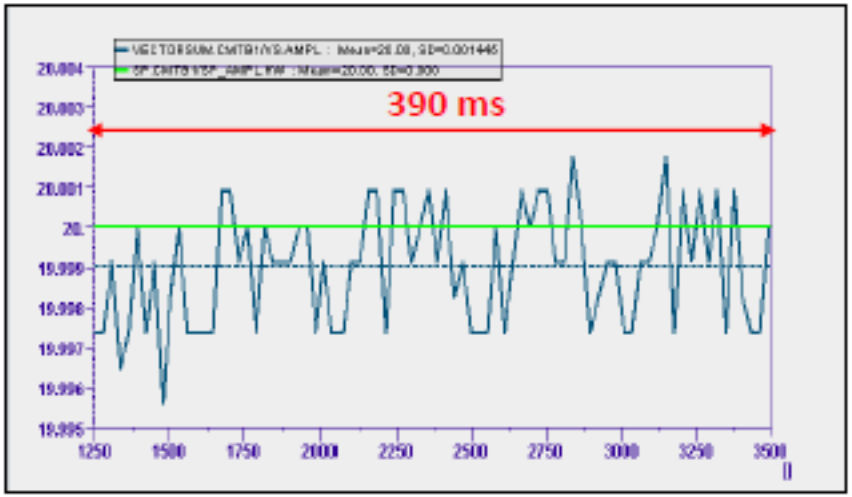
> IOT prototype HV rise transient – compensated by LLRF feedback



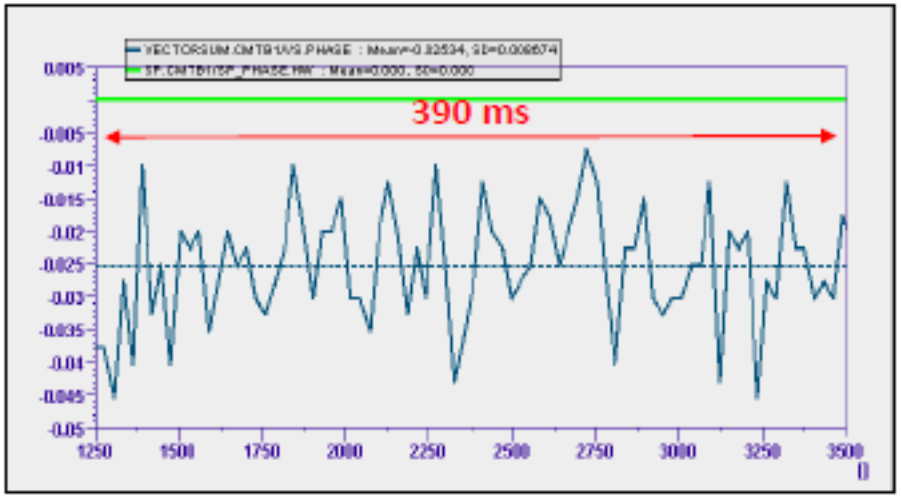
Results – long pulse operation

Test Results, cont.:

2. Stability of the VS for 7 cavities operating in lp mode was find to be the same as for the cw operations. Below is an example at $<E_{acc}>$ = 3.5 MV/m, DF=43%, flat top 390 ms, filling time 110 ms, RF-pulse rep. rate 1 Hz, piezo bias on and the RF-feedback **on.**



Standard Deviation for Amplitude = **7.2E-5**



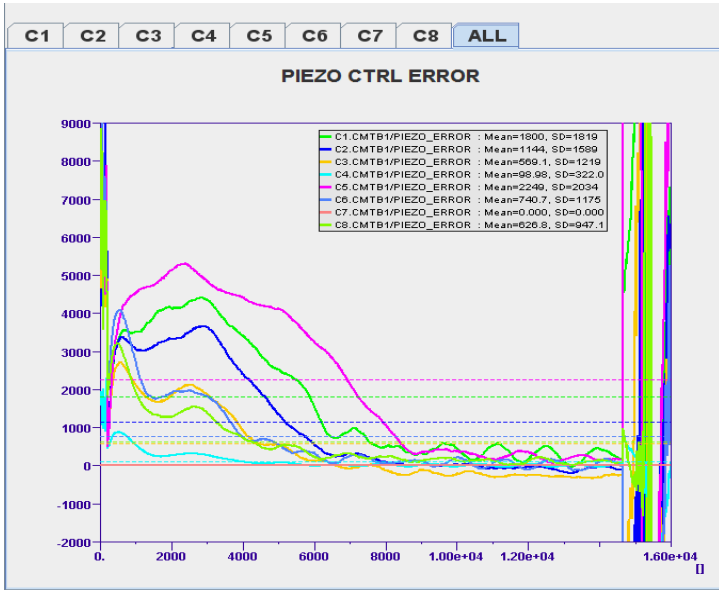
Standard Deviation for Phase = **0.0087°**

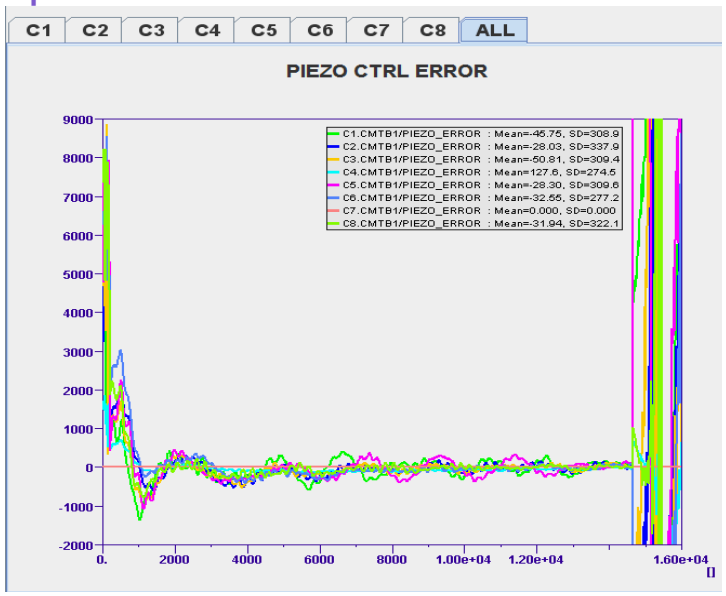
3. The same stability was observed for higher gradients, $<E_{acc}>$ = 6.5 MV/m, and slightly shorter flat-top of 356 ms.

Courtesy J. Sekutowicz

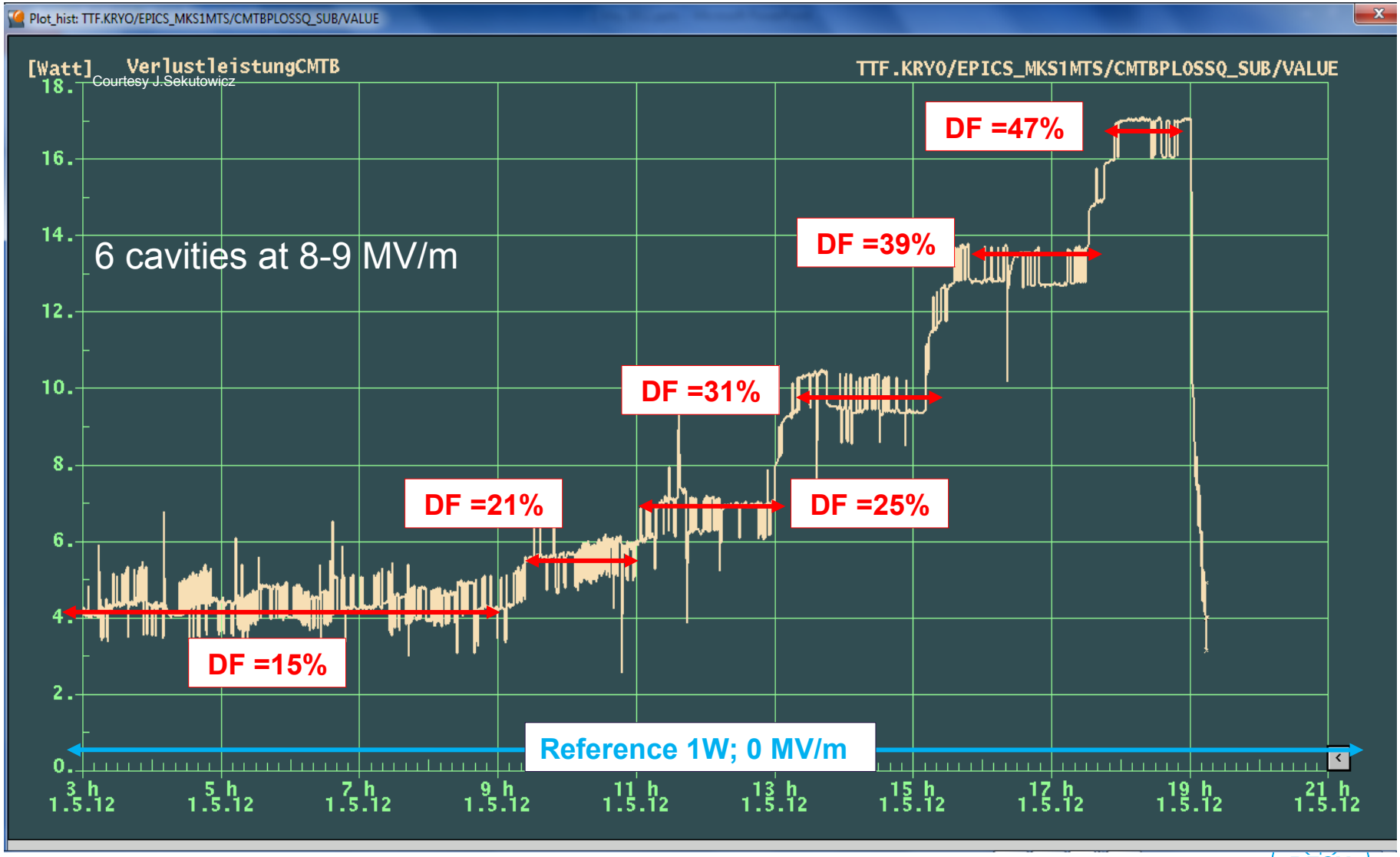
Results – long pulse – piezo perfromance

- Piezo feedback operates well for cavities at 8MV/m gradients,
- Cavities were in resonance with static error of about 2%
- Compensation of Lorentz Force Detuning was possible during cavity fill time
- Still some field for improvement → optimization of feedback parameters,
- Parasitic ~50 Hz oscillations (most probably form cryo pumps) has not been completely suppressed,
- Piezo feedback and LLRF feedback cooperation is still an issue to be solved

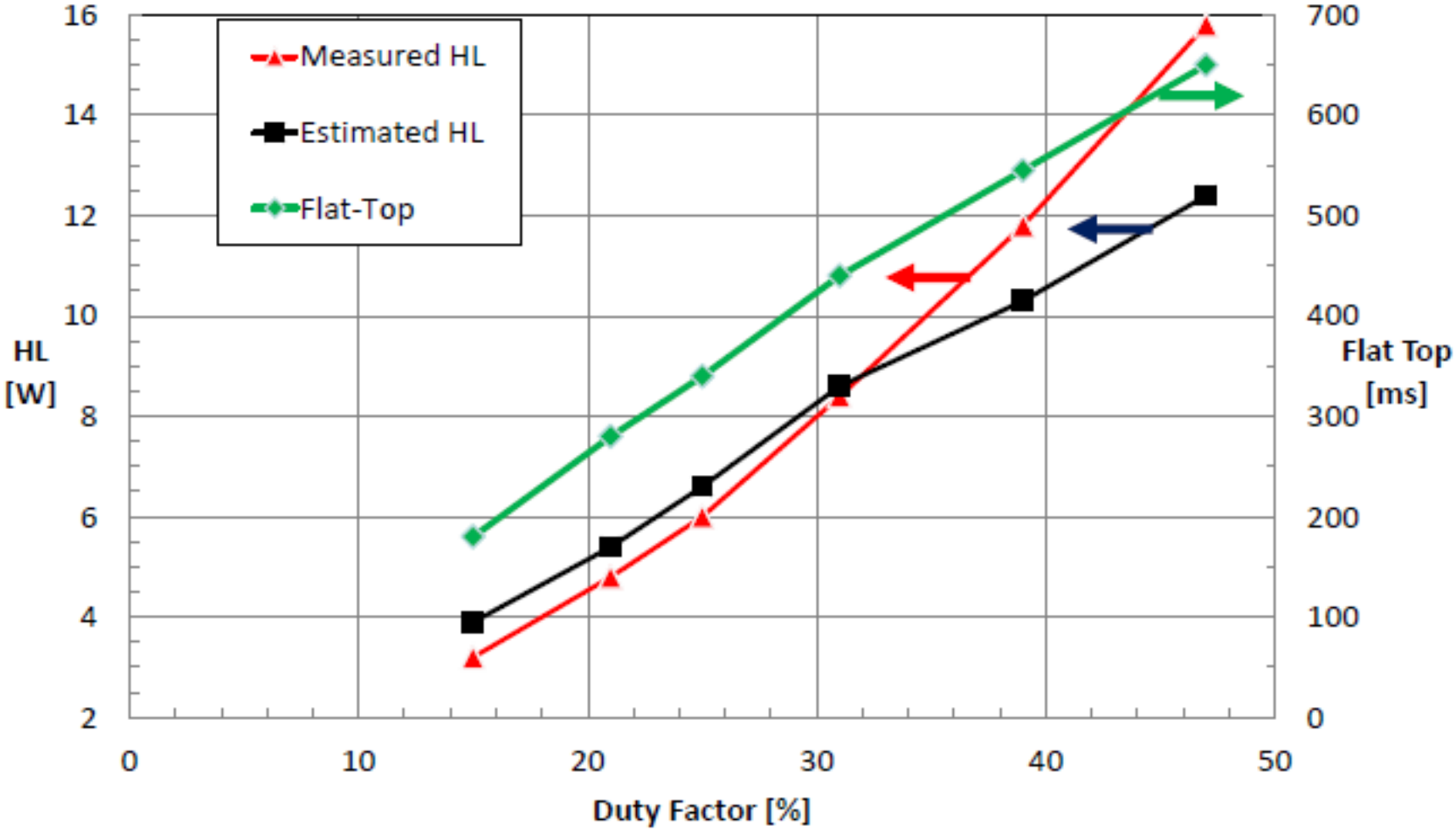




Results – measured Heat Load



Results – measured Heat Load

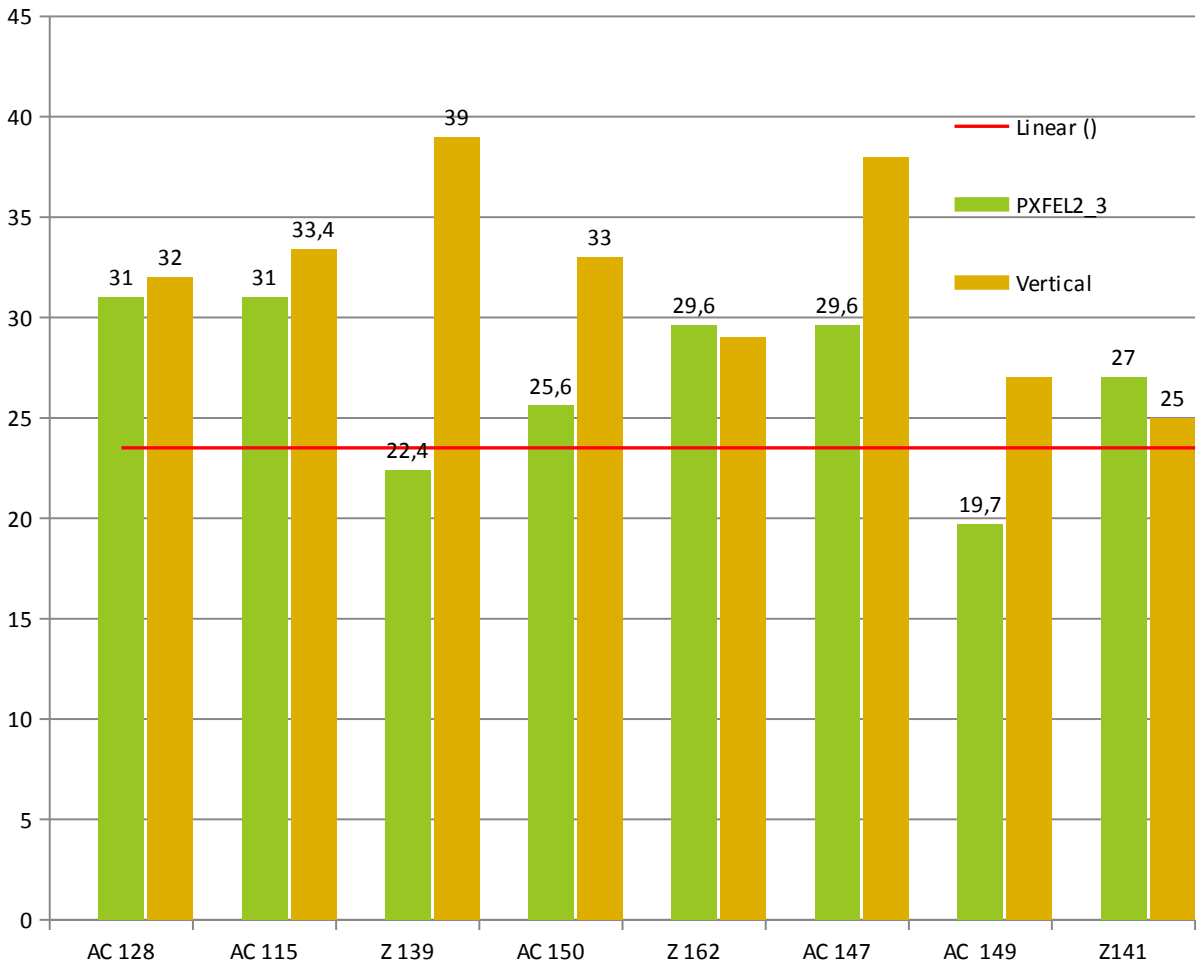


Outlook and future

- Successful
  - Long Pulse and CW operation with gradients up to 8-9MV/m (fulfilled XFEL specs – in-loop measurement),
  - Well performing piezo loop for keeping cavity in resonance,
  - The measured heat load below assumed limit,
- Still to be improved:
  - Piezo feedback parameters optimization (higher gradients – more demanding control – keep in mind 80 Hz cavity bandwidth),
  - IOT reveals high nonlinear behavior (nonlinear transfer characteristics) that might limit feedback performance – linearization algorithms will be implemented,
  - LLRF system performance cross check with former VME based control system (out of the loop results for confirmation).

Outlook and future

> Future activities (April-May 2013)



Courtesy M.Wiencek

Thank You

Thank You

Acknowledgments to all involved with the CW test:

V. Ayvazyan, J. Branlard, M. Ebert, N. Engling, J. Eschke, T. Feldmann, A. Goessel, W. Jalmuzna, D. Kostin, M. Kudla, F. Mittag, W. Merz, C. Müller, R. Onken, A. Piotrowski, K. Przygoda, I. Sandvoss, J. Sekutowicz