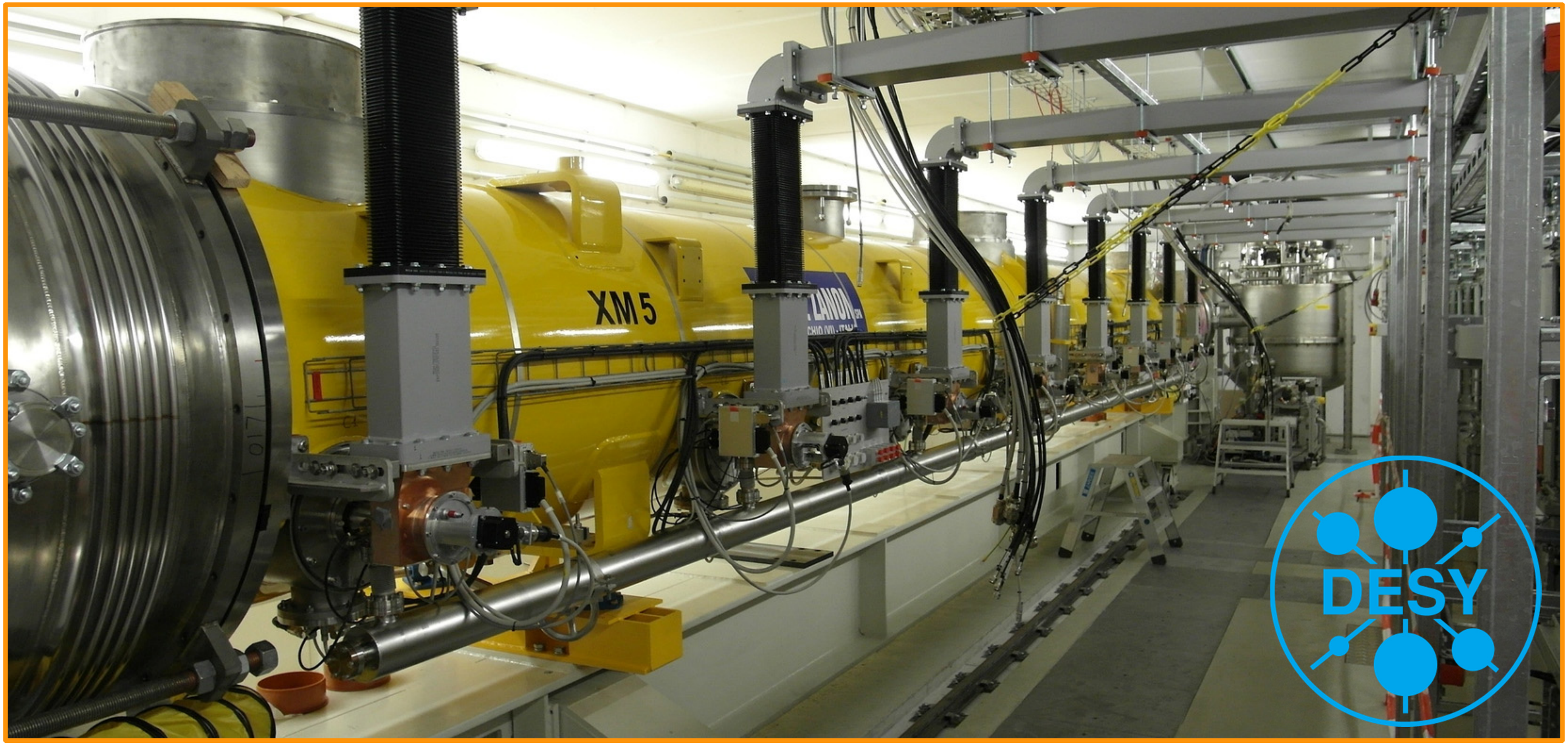
LCLS-2 Cavity and Cryomodule Test Workshop 2015

Denis Kostin, MHF-SL, DESY. 29.10.2015

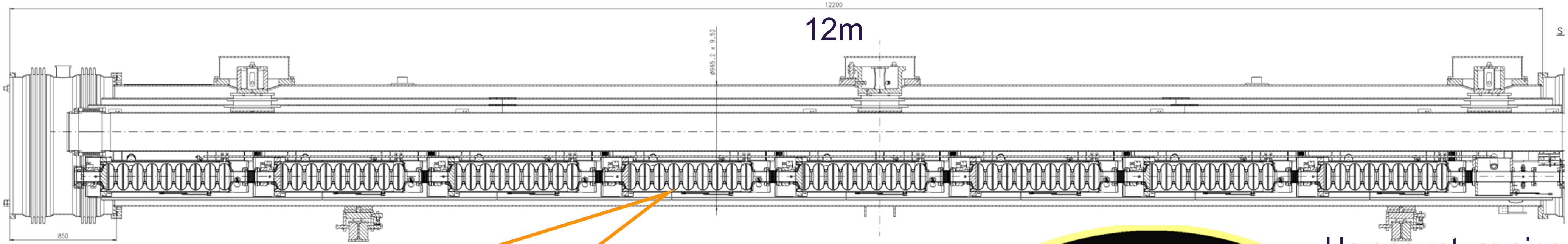
Cryo-Module test experience at DESY for the European XFEL

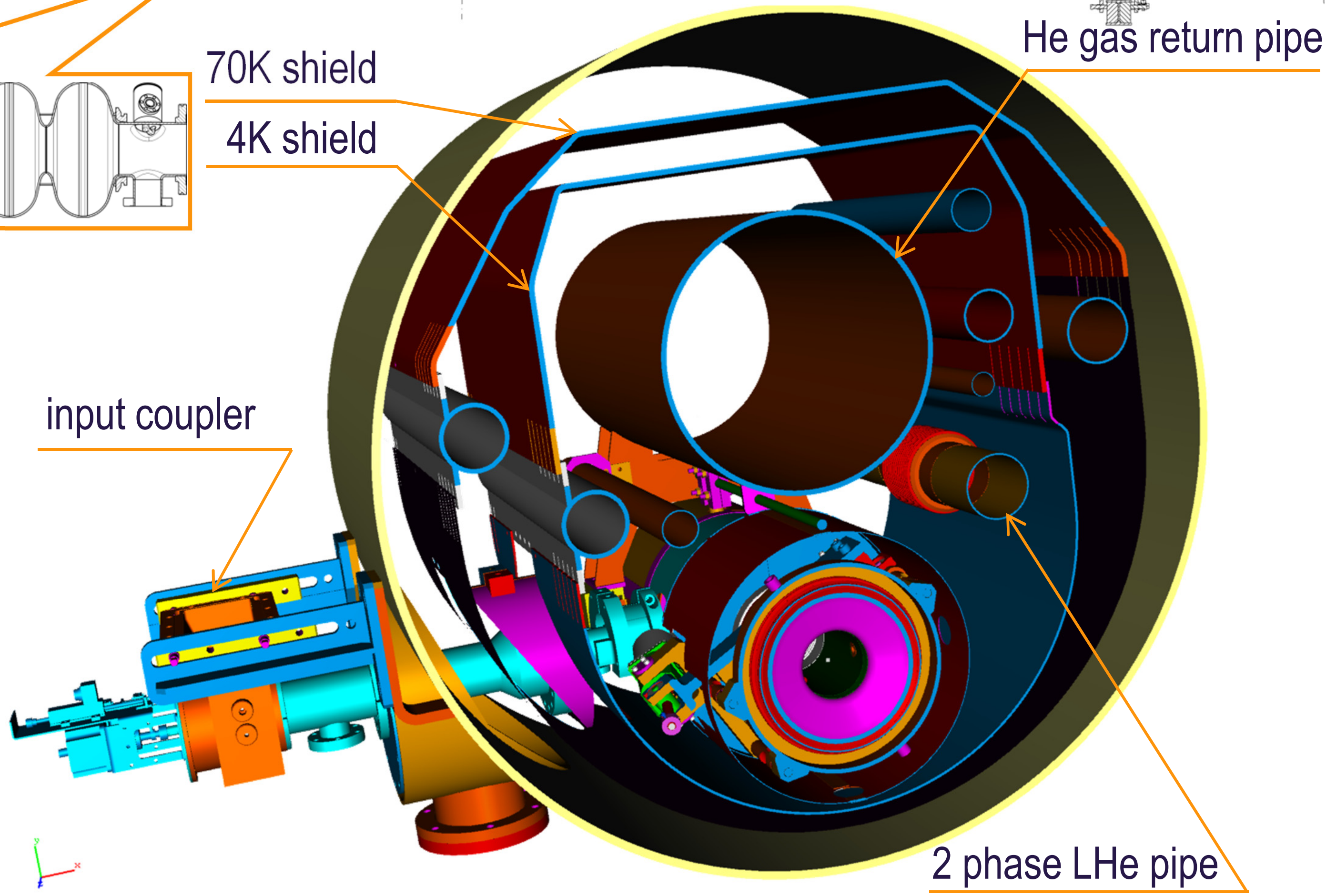


Outline

1. E-XFEL CryoModule Layout
2. CM Test Stand AMTF
3. CM Test Program and Procedures
4. CM Test Results and Data
5. Summary

1.1 E-XFEL Module Layout

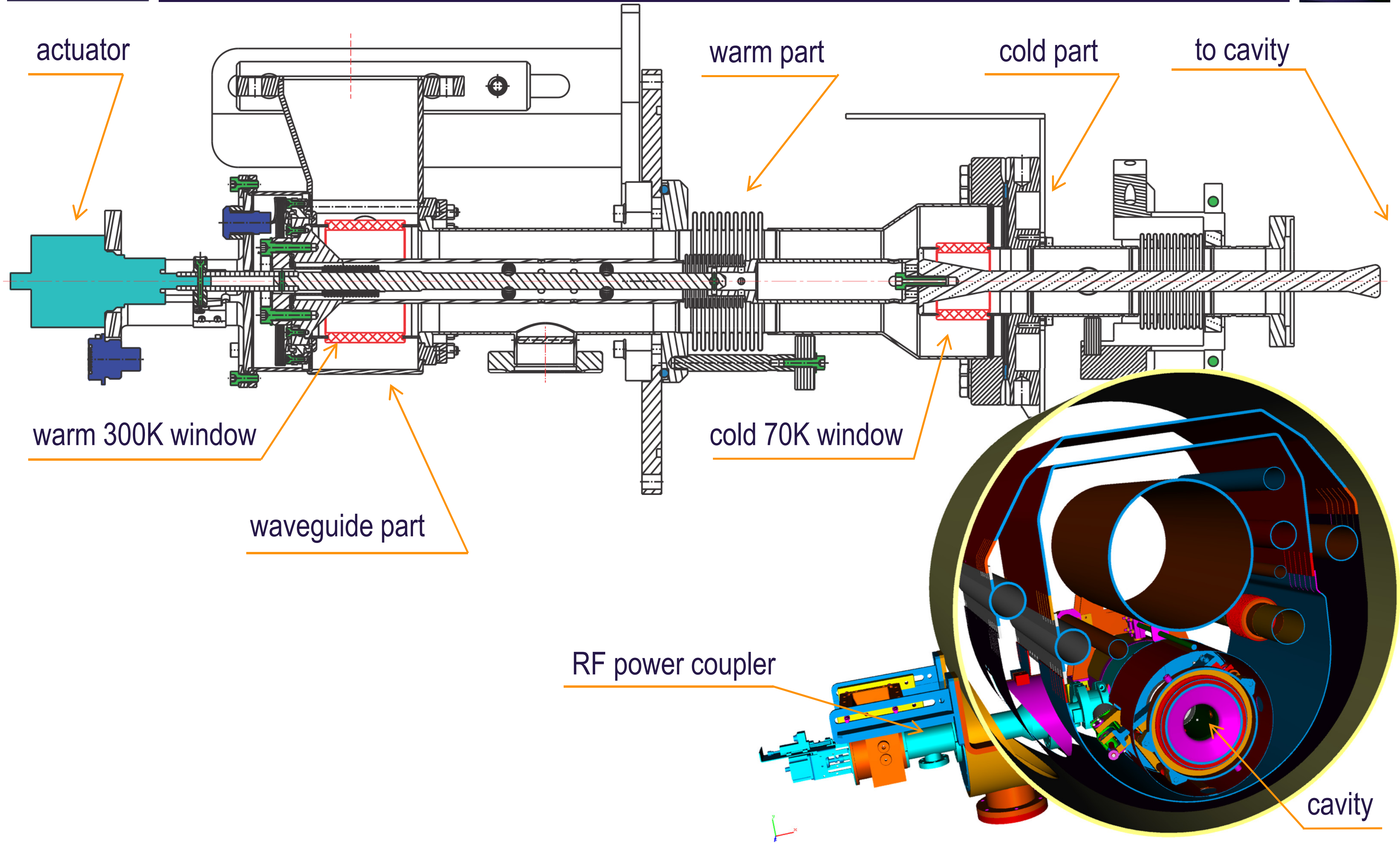




Cavity type	TESLA
Number of cavities	8
Cavity length	1.035 m
Operating frequency	1.3 GHz
R/Q	1030 Ω
Accelerating Gradient	20..31 MV/m
Quality factor	10^{10}
Q_{ext} (input coupler)	4.6×10^6
Operating temperature	2 K

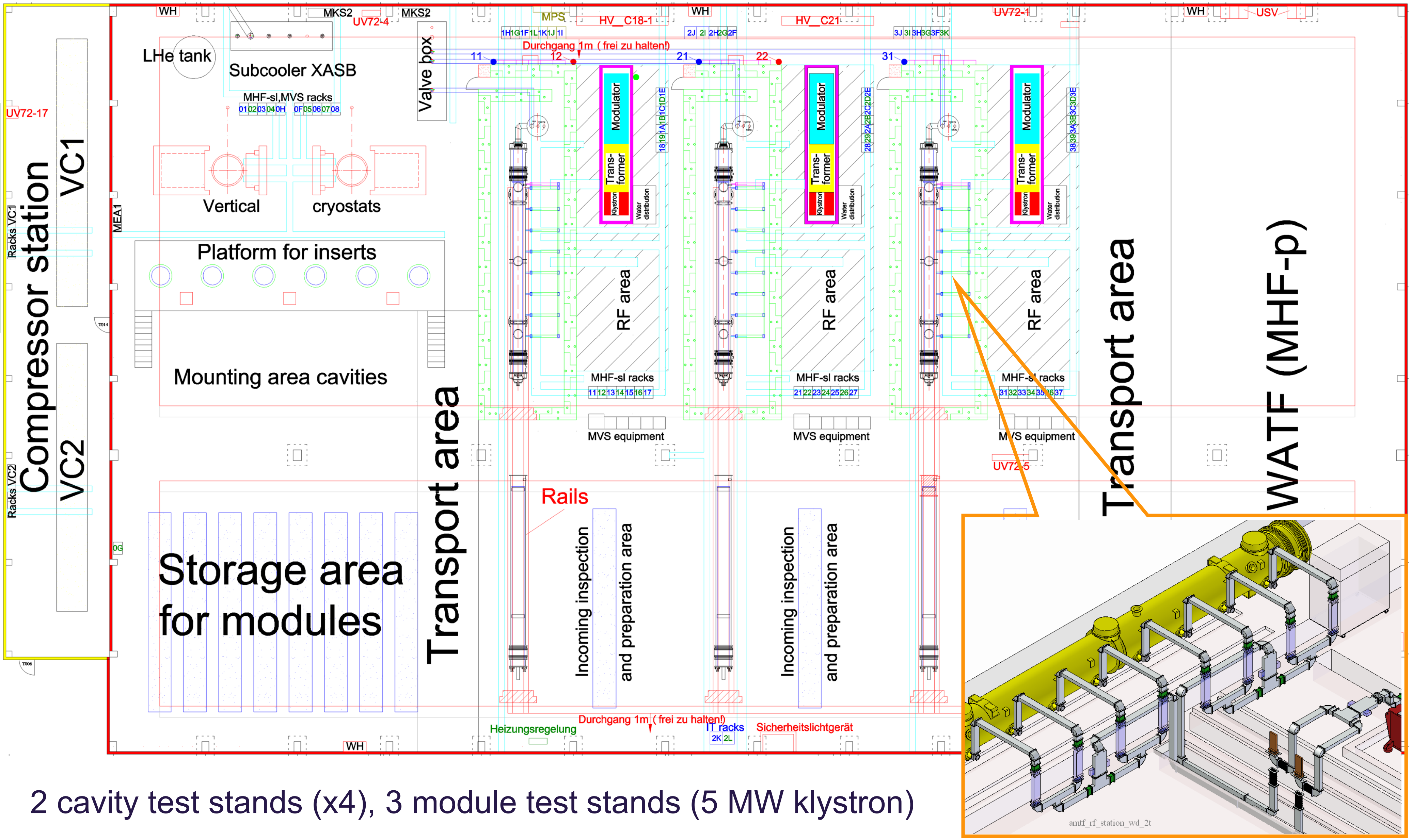
LHe cooling 2K / 31mbar
HERA cryoplant is used

1.2 E-XFEL Module RF Power Coupler



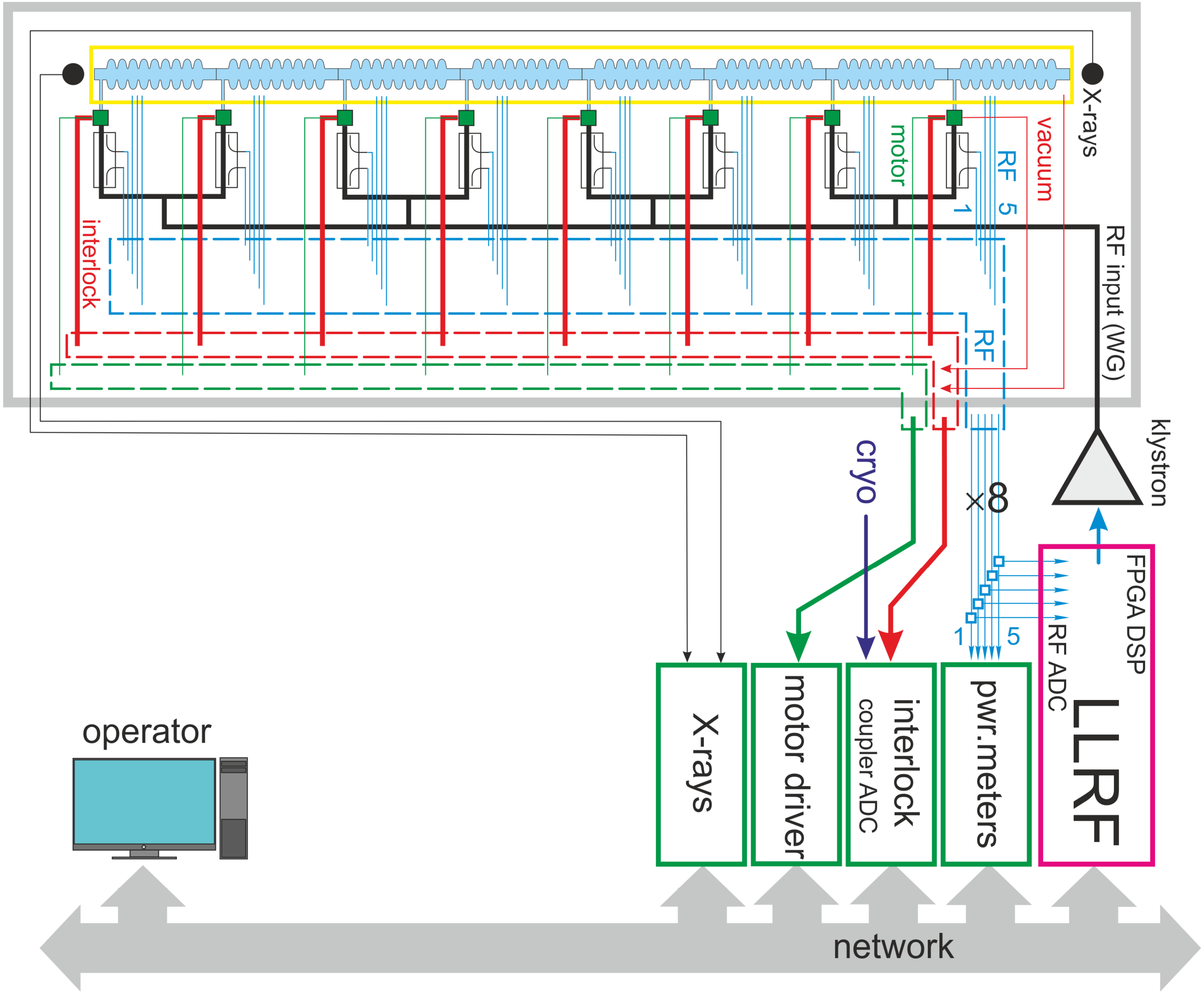
2.1 AMTF Overview

2.2 AMTF Layout



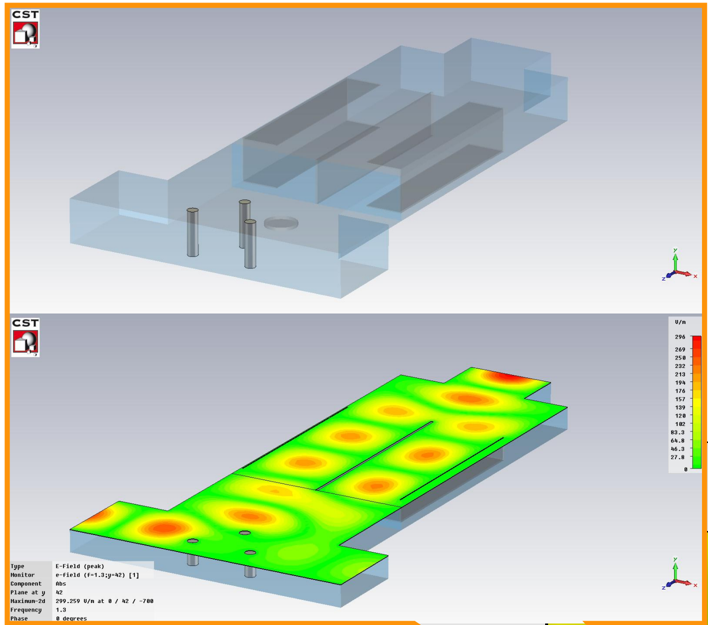
2 cavity test stands (x4), 3 module test stands (5 MW klystron)

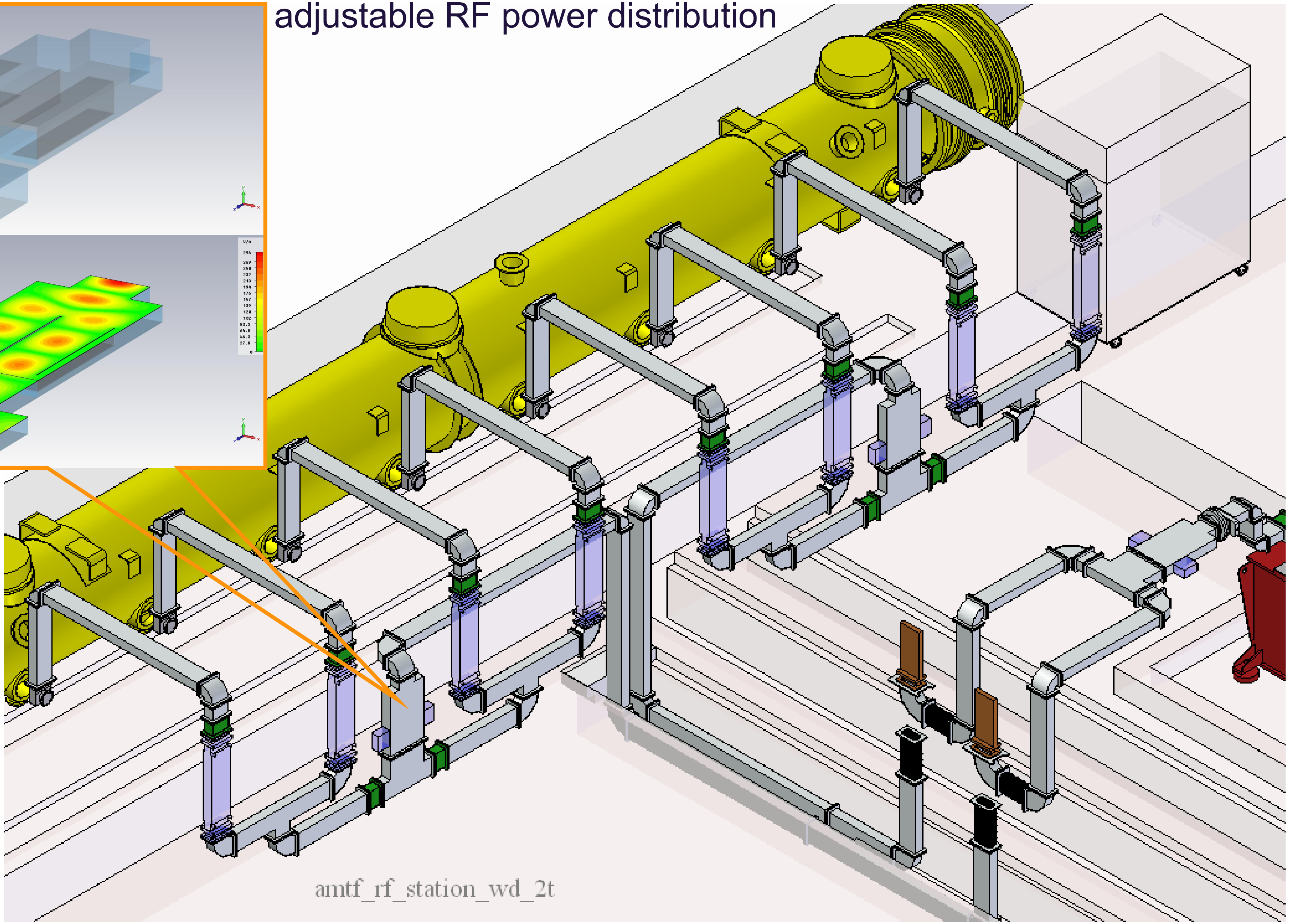
2.3 CM RF Test Diagram



2.4 CM Test Waveguide RF Power Distribution

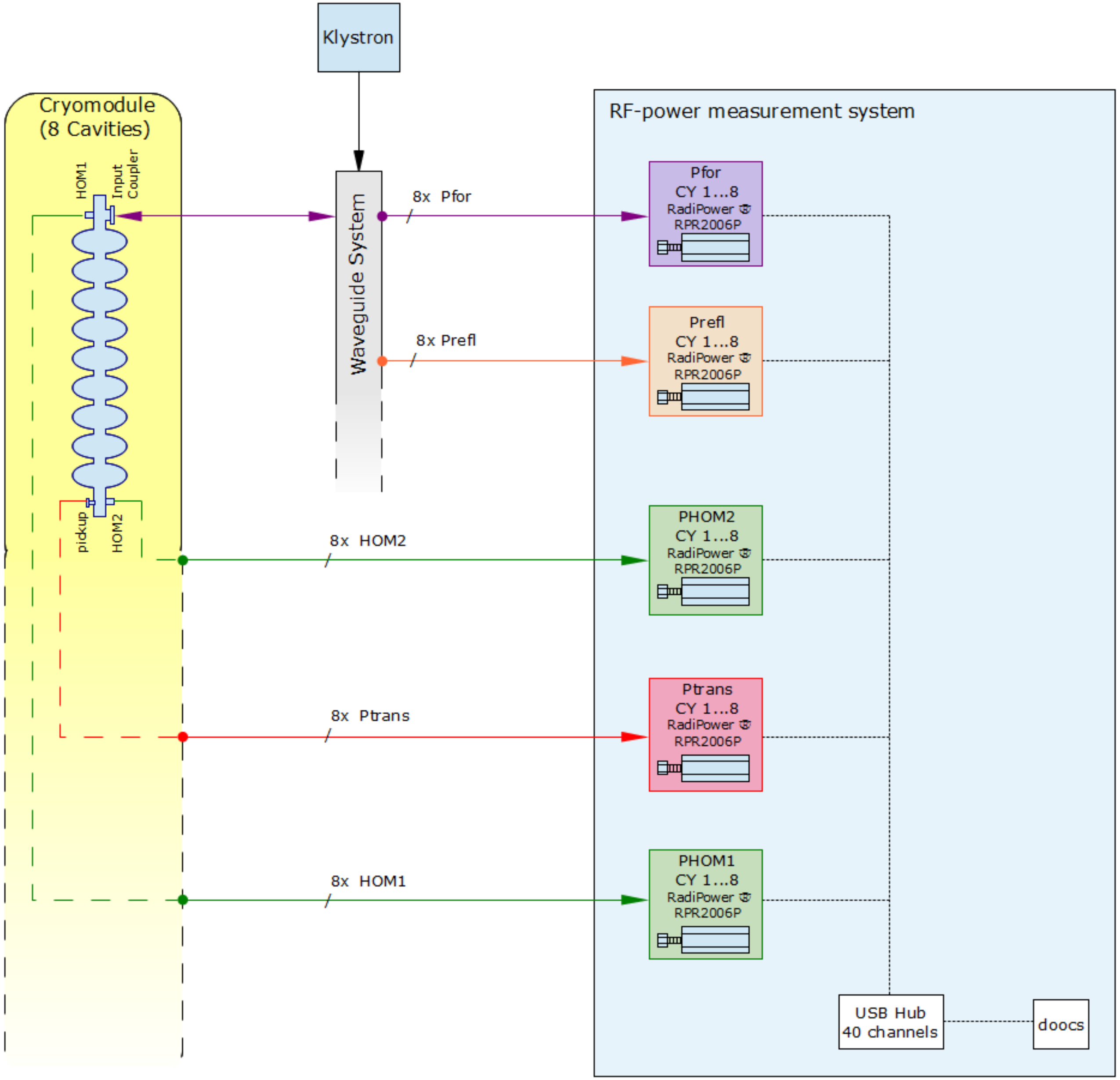
adjustable RF power distribution





V. Katalev

2.5 CM RF Power Measurement



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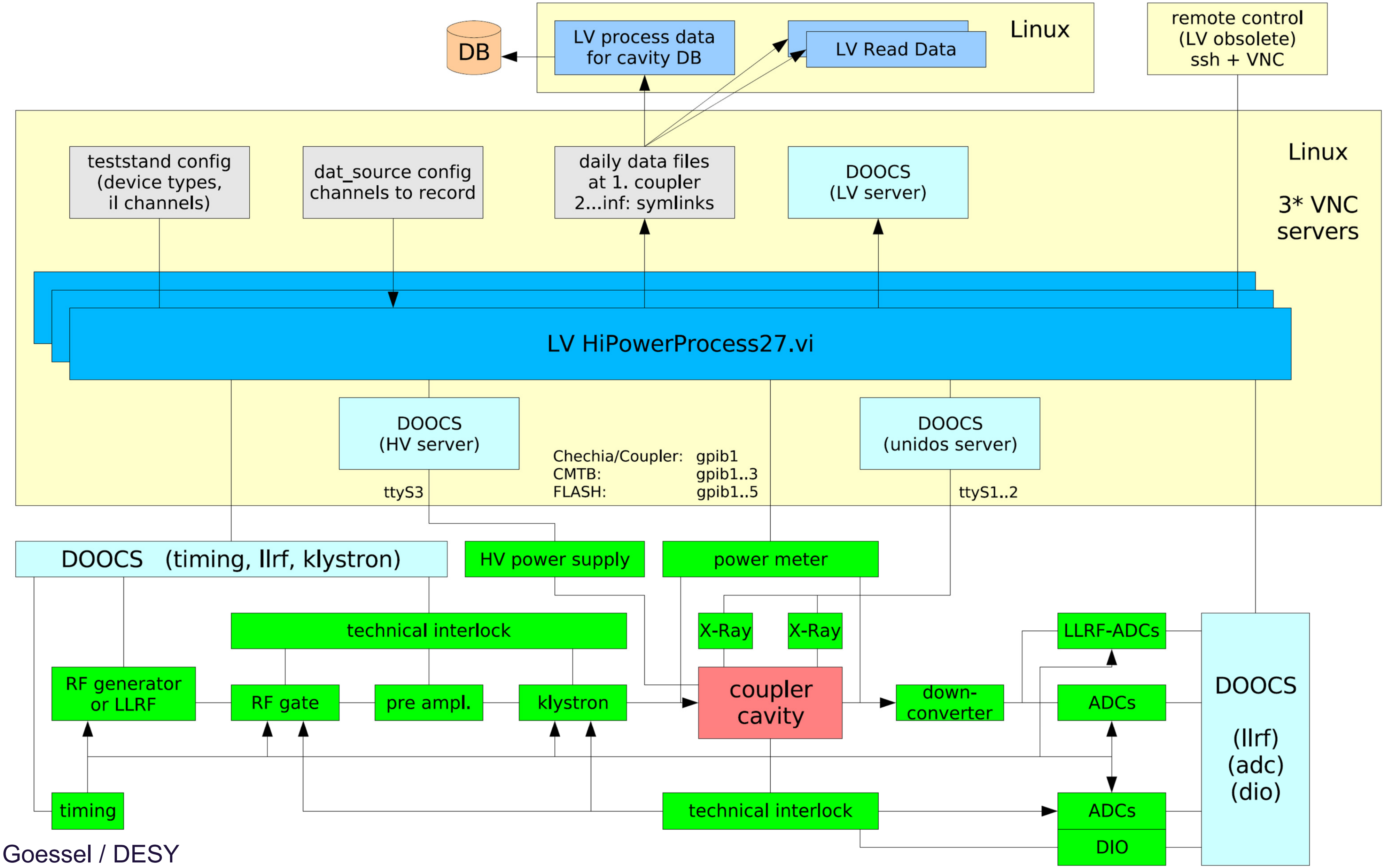
2.6 CM RF Conditioning / Data / Controls



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3.1 CM Test Steps (1)

1. RF Cables Calibration.
   - TDR cables check
   - Dir.Couplers / Circulators: get calibration data.
   - Calibrate RF power measurement cables with attenuators at 1.3 GHz (P for/ref att. ~ 93 dB, P trans/HOM ~ 40 dB)
   - Calibrate RF power measurement cables with attenuators at 1…4 GHz (optional)
   - Make RF calibration summary table
2. Technical Interlock / Sensors.
   - Check the sensors (e-, Spark, Temperature)
   - Set the hardware interlock thresholds
   - Check the interlock
3. RF source / Waveguides / LLRF.
   - Klystron / LLRF check on the load
   - WGs visual check
   - System check / RF leak check at low power (1 kW pro coupler)
4. Warm Input RF Couplers Conditioning (all / 1234 + 5678).
   - Run the standard conditioning program:
     20, 50, 100, 200, 400 μs pulse lengths up to 750kW,
     800, 1300 μs pulse lengths up to 600 kW, 2 Hz rep.rate.
     (If the klystron gives not enough of RF power divide the system into the successive tests in such a way that each coupler will be conditioned up to 750kW.)

3.1 CM Test Steps (2)

5. Cooldown to 2K.
6. Cavities Fundamental Spectra measurements.
   - Measure the fundamental mode spectra (before tuning at 2K)
   - Calibrate the cold RF cables at 2K and 1.3 GHz
7. Cavities Tuners Test and Cavities Tuning.
   - Test the cavities step-motor frequency tuners
   - Tune the cavities to the 1.3GHz using the Network Analyzer
8. Couplers Q_{load} measurement.
   - Measure the Q_{load} vs antennae positions, check $Q_{load.MIN}$ and $Q_{load.MAX}$ using the Network Analyzer
   - Set $Q_{load} = 4.6\times10^6$ for each coupler, adjust π-mode frequency
9. Cavities HOM Spectra measurements.
   - Measure the cavities HOMs spectra and Q_{load} (cavities tuned)

3.1 CM Test Steps (3)

10. Cavities On Resonance.
    - Cavities fine-tuning to the 1.3GHz using LLRF system
    - Q_{load}, K_t calibration ($E_{acc}=k_t\times(P_{trans})^{1/2}$)
    - $Q_{ext.HOM}$ at 1.3 GHz measurement with low RF power ($Q_{ext.HOM}$ at 1.3 GHz must exceed 10^{12}). After this measurement HOM couplers must be disconnected from the RF power meters and connected to RF loads.
11. Cold Couplers and Cavities Conditioning (on resonance).
    - Short RF pulse conditioning: 20, 50, 100 μs pulse lengths up to 700kW (max.power), 2 Hz rep.rate, on resonance.
12. Single Cavities Measurements.
    - Detune all cavities except the one under test.
    - Short RF pulse test at 2K on resonance (100 .. 500 μs pulse lengths up to 700kW, 2 Hz rep.rate), first cavity power-up, coupler / cavity conditioning (HPP).
    - $E_{acc.MAX}$ measurement at 2 [10] Hz rep.rate with 750 + 100 μs short flat-top pulse. MP conditioning.
    - Flat-top 750 + 650 μs pulse measurements at 10 Hz rep.rate with cryo losses (Q_o) if measurable and radiation measurements.
    - Investigate the cavities limits at 10 Hz rep.rate.

3.1 CM Test Steps (4)

13. Module Performance Measurement.
    - Module $E_{acc.MAX}$ measurement at 2 [10] Hz rep.rate
    - Module accelerating gradient measurement at 10 Hz rep.rate with cryo losses (Q_o) and radiation measurements
    - Radiation / Dark Current measurements.
    - WG power redistribution possibilities check in case of too different cavities limits ($\Delta E_{acc.MAX}$ > 5 MV/m)
14. Cryo system performance test (if needed).
    - Static Cryogenic Losses measurement, temperature measurements.
    - Cold Magnet Tests.
    - Cool-down cycles.
15. LLRF and piezo test.

CM Test Documents (EDMS):

1. CM Incoming Inspection
2. CM Final Test Report
3. CM Outgoing Inspection
4. Non-Conformity Reports

3.2 CM Test Data

1.	Cold Cables Attenuations (A_t, $A_{HOM1/2}$) at 2K	8 cavities
2.	Cavity Probe Calibration: k_t	8 cavities
3.	Coupler Q_{load} [operating value]	8 cavities
4.	Coupler $Q_{load.MIN}$ / $Q_{load.MAX}$	8 cavities [couplers]
5.	$Q_{ext.probe}$, $Q_{ext.HOM1/2}$	8 cavities
6.	frequency / spectra at 2K before tuning	8 cavities
7.	Tuner steps N_{tuner} to 1.3 GHz	8 cavities
8.	$E_{acc.X\text{-}start}$ (single)	8 cavities
9.	$E_{acc.X\leq 1e\text{-}2}$ (single)	8 cavities
10.	$E_{acc.MAX}$ (quench/power limit, single)	8 cavities
11.	$E_{acc.op}$ (operating limit, single) *	8 cavities
12.	$E_{acc.WG}$ XFEL binary distribution gradient	8 cavities
13.	E_{acc} FT pulse structure: pulse lengths t_{rise}, t_{FT} [µs], $E_{acc.FT.min}$ and $E_{acc.FT.max}$	8 cavities
14.	X-rays ($E_{acc.MAX}$) gun/dump	8 cavities
15.	$\langle E_{acc.MAX}\rangle$, $\langle E_{acc.op}\rangle$, $\langle E_{acc.WG}\rangle$	module
16.	$V_{module} = \Sigma E_{acc.WG}$, module voltage	module
17.	$P_{cryo}(E_{acc})$ and $Q_0(E_{acc})$ [pulse data]	module
18.	X-rays(E_{acc})	module
19.	E_{acc} FT pulse structure: pulse lengths t_{rise}, t_{FT} [µs], $E_{acc.FT.min}$ and $E_{acc.FT.max}$	module
20.	HOM spectra $Q_{ext}(f_{HOM})$ at 2K, tuned cavities	8 cavities

* $E_{acc.op} = \min\{E_{acc.X<1e\text{-}2}, E_{acc.MAX.BD}\text{-}0.5[MV/m], E_{acc.MAX.PWR}\}$

3.3 CM Test Flow (remarks)

Measurement flow:

1. Coupler conditioning (warm) 2Hz.
2. Cooldown.
3. Cavities Fundamental Spectra measurement.
4. Cavities tuning. Q_{load} measurement and tuning.
5. Cavities HOM Spectra measurement.
6. Cavities calibration: k_t and Q_{load}, $Q_{ext.probe}$, $Q_{ext.HOM1/2}$ (8 cavities parallel)
7. Cold conditioning / HPP (short pulse) / single cavities.
8. FT measurement: single cavities (with detuning), no Q_0 measurement.
   RF power, E_{acc}, X-rays measured. 10Hz.
   FT pulse $E_{acc.FT.min}$ and $E_{acc.FT.max}$ are calculated/measured from FT pulse.
9. FT measurement: all cavities (up to the module limit) with Q_0.
   RF power, E_{acc}, X-rays, P_{cryo} measured. 10Hz.
   FT pulse $E_{acc.FT.min}$ and $E_{acc.FT.max}$ are calculated/measured from FT pulse.
10. Piezo test: Loretz force detuning [Hz] vs E_{acc} [MV/m],
    without/with piezo compensation.

Optimized test procedure takes 13..15 days.

Delays are caused by non-conformities:

- (cryogenic + vacuum) leaks (mainly at temporary connections to test stand)
- warm coupler part

3.4 CM Test Procedures

Defined and documented CM Test Procedures:

	Procedure name
1	Enabling of the Personal Interlock
2	Disabling of the personal interlock
3	Switching ON/OFF modulator and klystron. Locking modulator
4	Check the hardware interlock thresholds, set technical interlock to warm mode
5	Set technical interlock to cold mode
6	Vacuum level check before start of coupler conditioning
7	Warm input RF Coupler conditioning
8	Coupler conditioning during cooldown
9	Cavities fine tuning to 1.3 GHz using LLRF system
10	Set the cavity input power limitation
11	Q_{load}, K_t calibration, $Q_{load \cdot HOM}$ at 1.3Ghz with low RF Power
12	Flat - top cavity measurement at 10 Hz repetition rate
13	Cryomodule High RF Power and Heat Loads measurements
14	Detune cavities
15	LLRF check
16	LLRF test

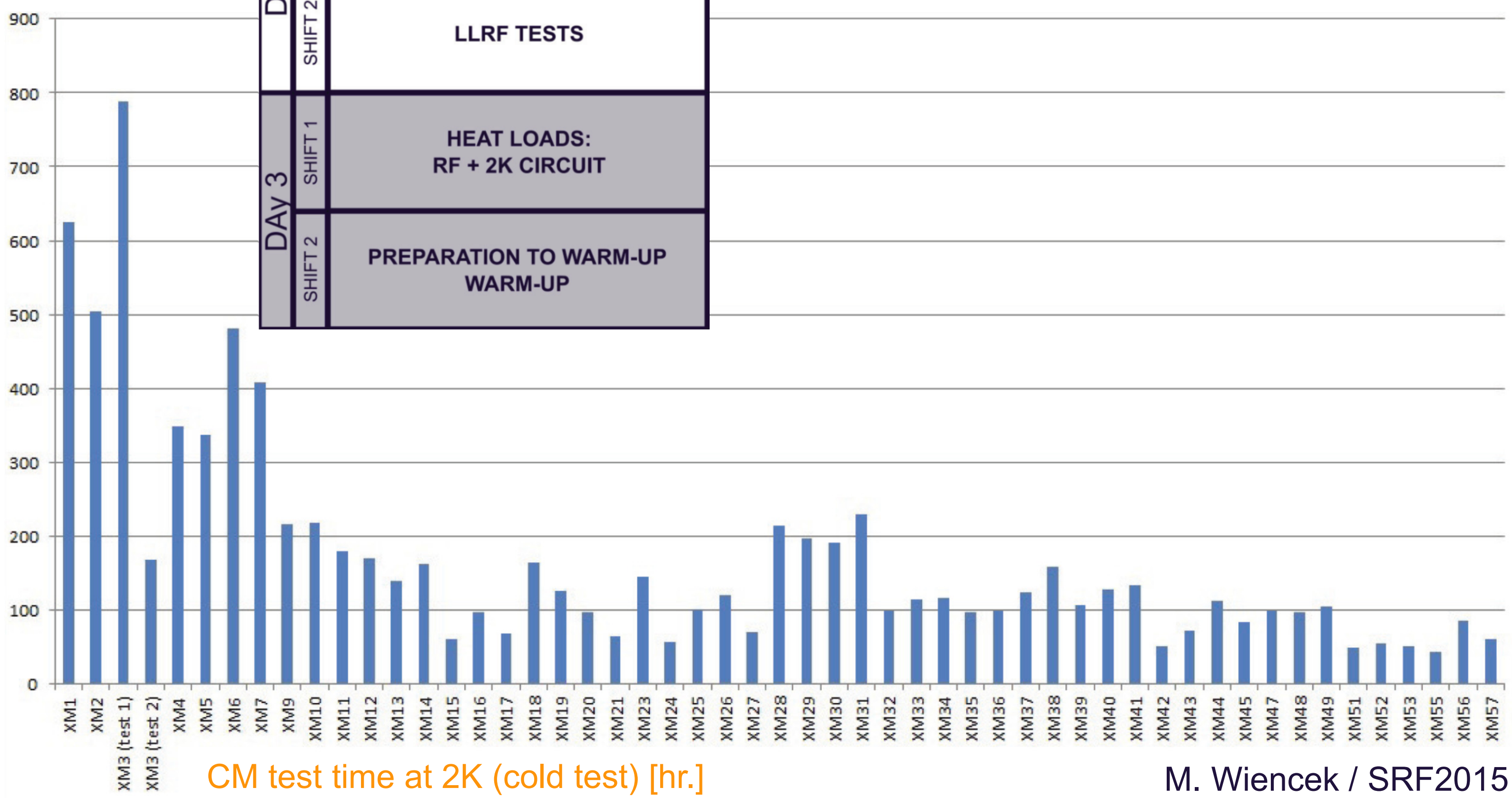
3.5 CM Test Flow (improvements)

MONDAY	SHIFT 1	LOW POWER MEASUREMENTS
MONDAY	SHIFT 2	LOW POWER MEASUREMENTS CRYOMODULE CALIBRATION FLAT TOP MEASUREMENTS
TUESDAY	SHIFT 1	FLAT TOP MEASUREMENTS
TUESDAY	SHIFT 2	FLAT TOP MEASUREMENTS LLRF TESTS
WEDNESDAY	SHIFT 1	HEAT LOADS: MAGNET + SHIELDS
WEDNESDAY	SHIFT 2	HEAT LOADS: MAGNET + SHIELDS
THURSDAY	SHIFT 1	HEAT LOADS: RF + SHIELDS
THURSDAY	SHIFT 2	HEAT LOADS: RF + SHIELDS
FRIDAY	SHIFT 1	HEAT LOADS: RF + 2K CIRCUIT
FRIDAY	SHIFT 2	LLRF TESTS PREPARATION TO WARM-UP WARM-UP

change

DAY 1	SHIFT 1	LOW POWER MEASUREMENTS ROUGH CALIBRATION
DAY 1	SHIFT 2	FLAT TOP MEASUREMENTS-1 RUN CCC PROBES CRYOMODULE CALIBRATION
DAY 2	SHIFT 1	FLAT TOP - CONFIRMATION RUN
DAY 2	SHIFT 2	LLRF TESTS
DAY 3	SHIFT 1	HEAT LOADS: RF + 2K CIRCUIT
DAY 3	SHIFT 2	PREPARATION TO WARM-UP WARM-UP

The most time consuming steps of the original CM test procedure: HOM spectra, reaching thermal equilibrium of "cold cables" for calibration and a long heat loads measurement on shields. Improved CM test procedure shortens the test time at 2K almost by a factor of two.



CM test time at 2K (cold test) [hr.]

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3.6 CM LLRF Test

- **LLRF relevant parameters**
  - Lorentz force detuning constant
  - Microphonics behavior (resonances)
  - Loaded Q variations with gradients
  - Model: piezo diag -> detuning parameter (microphonics cancelation)
  - 8/9 π & 7/9 π mode of each cavity (-> controller!)
  - Changes of Q_L with gradient (thermal coefficients)
  - Calibration for piezo DC/AC (actuator & diag, switching)
  - Calibration stepper motor & hysteresis
  - Q_L range and opportunistic effects on cavity
- **Accept / reject accelerator module**
  - ✓ Lorentz force detuning exceeds normal value
  - ✓ Extreme sensitivity to microphonics
  - ✓ Abnormal behavior during fill/decay
  - ✓ Sudden QL variation (multipacting in couplers)
  - ✓ piezo / tuners not operable

J. Branlard

3.7 RF Power Coupler Warm Conditioning Steps

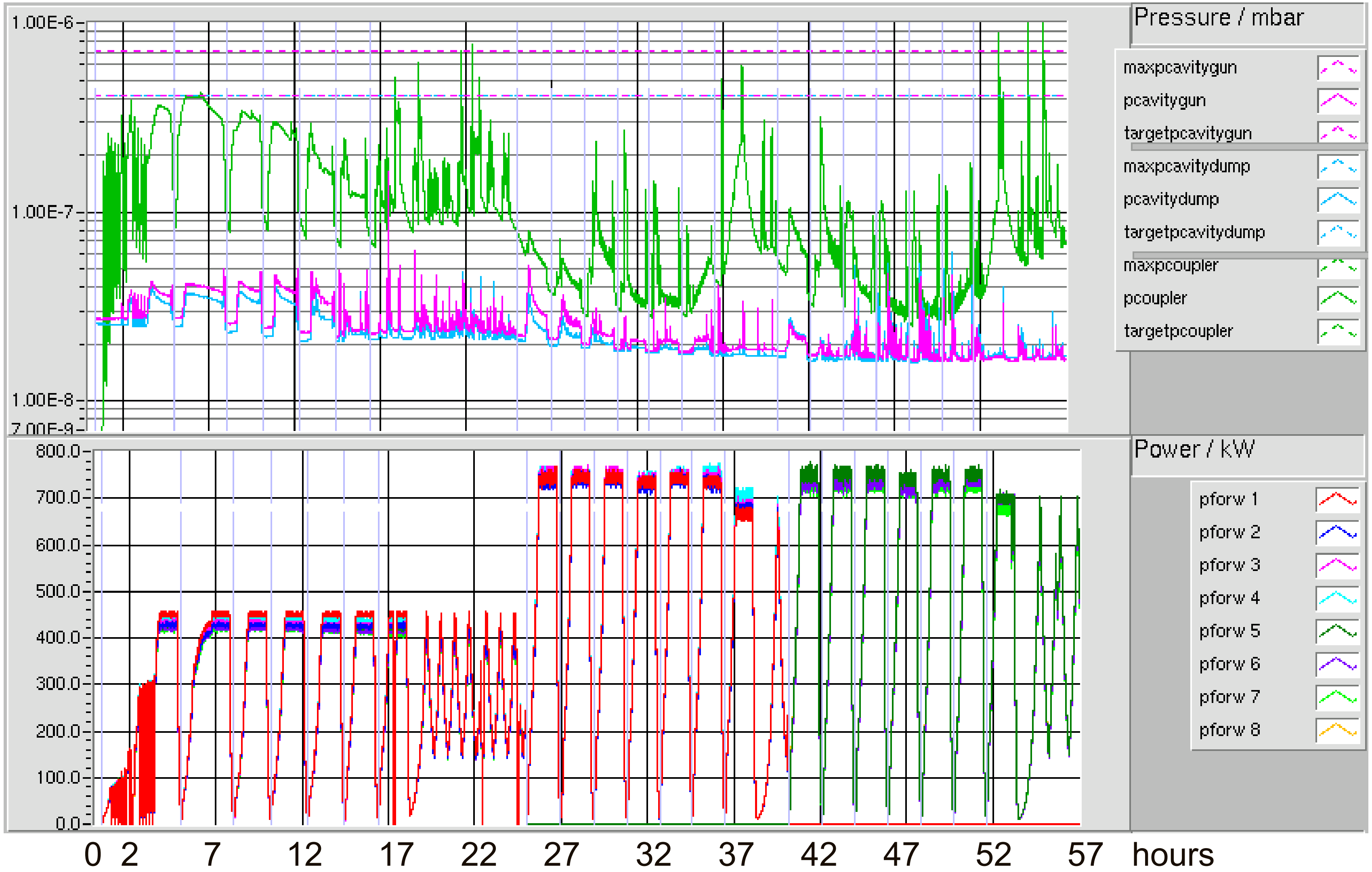
step N	pulse length [μs]	RF power [kW]	time [hr]	comments
1	20	750	5..50	activity onset 50kW
2	50	750	2..20	
3	100	750	2..20	
4	200	750	2..20	
5	400	750	2..20	
6	800	700	2..20	
7	1300	700	10..100	
8	1300	100..700	10	RF power sweep
total			50..200	normally 2..5 days

Warm coupler conditioning at AMTF is done in 3 steps (with 5MW total RF power):

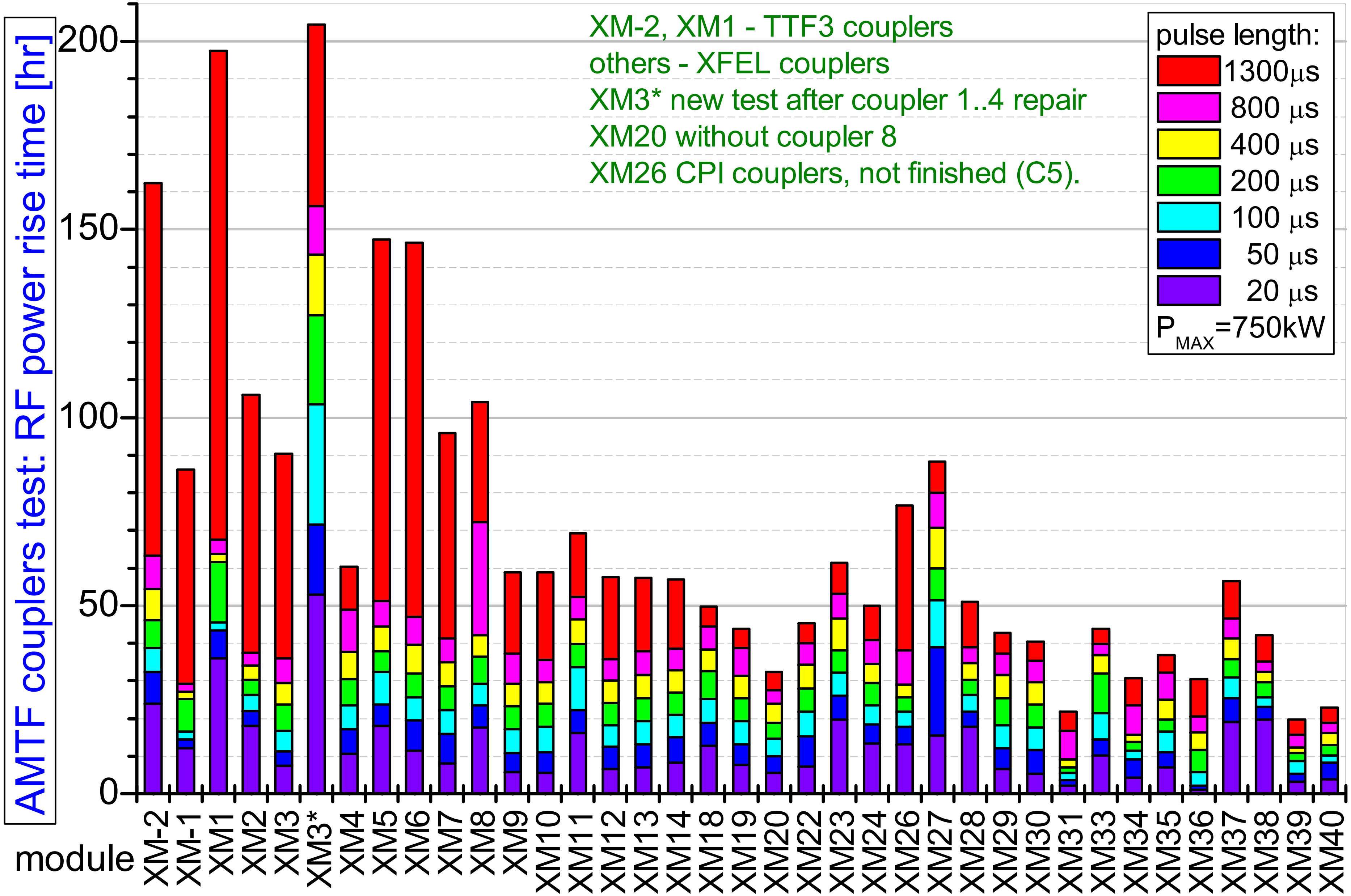
1. all 8 couplers are conditioned up to 450 kW;
2. couplers 1,2,3,4 are conditioned up to 750 kW;
3. couplers 5,6,7,8 are conditioned up to 750 kW.

4.1 Warm Coupler Conditioning History

Module XM14 warm couplers conditioning at AMTF (XATB2):



4.2 Warm Coupler Conditioning Time



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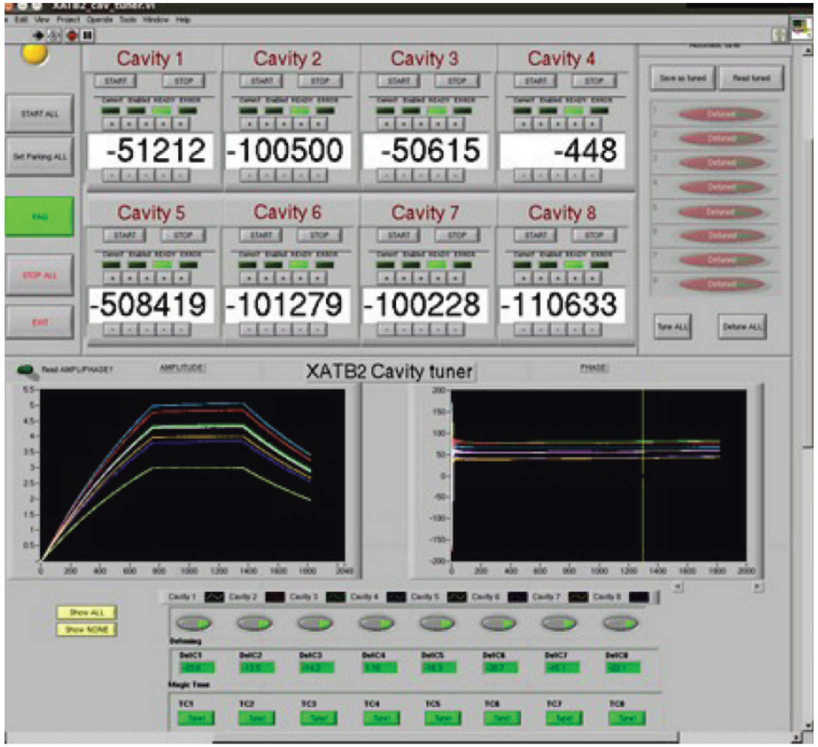
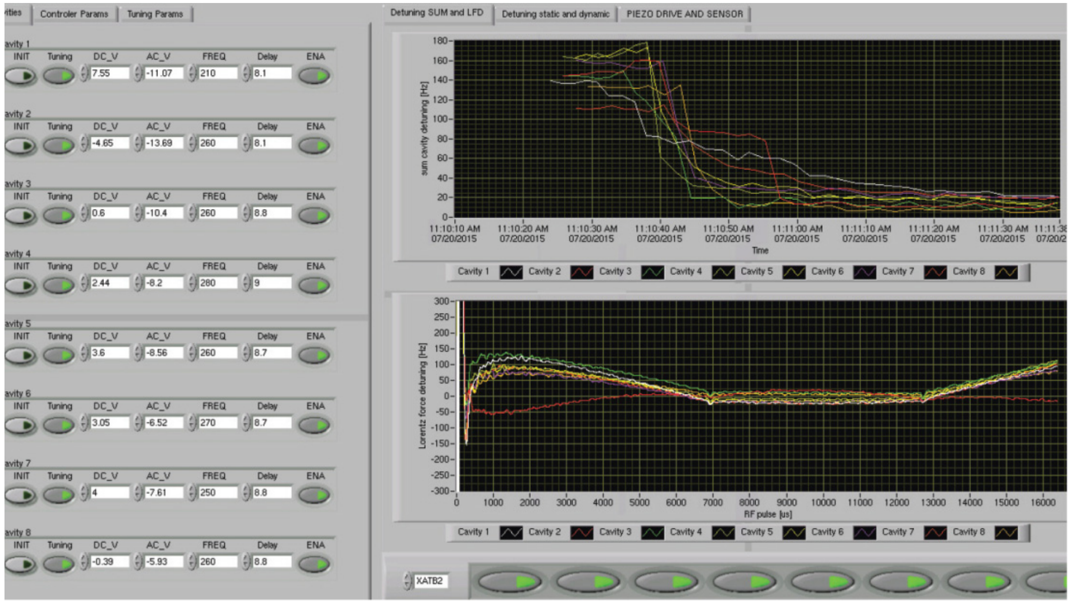
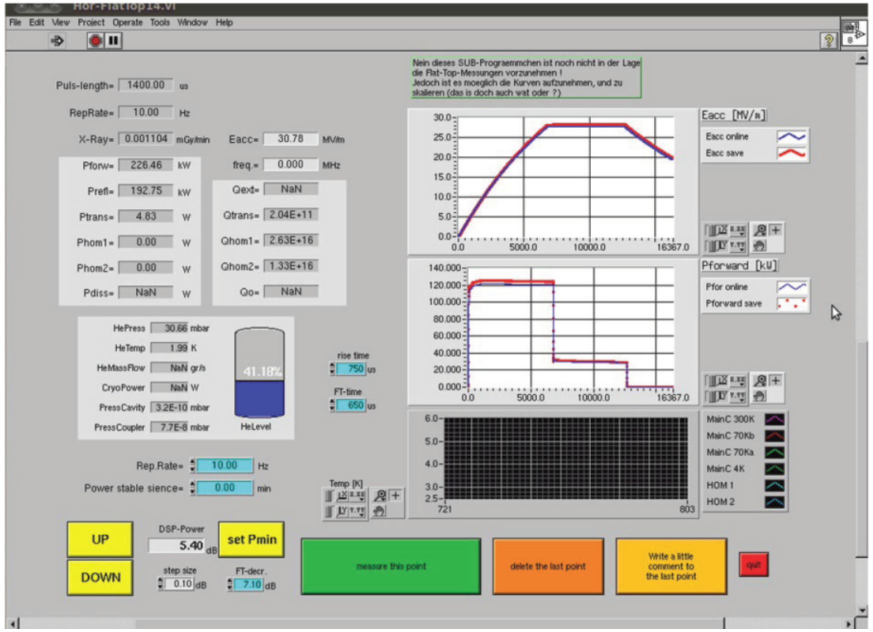
4.3 CM Cold Test / Software Tools



cavity frequency tuning



piezo tuning / operation



flat-top pulse test at 2K

custom software tools for the optimized test flow

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4.4 CM Cold Test / Calibration

Typical CM calibration data (module XM64)

	Cav 1	Cav 2	Cav 3	Cav 4	Cav 5	Cav 6	Cav 7	Cav 8
Q_{ext} [10^6]	4.61	4.60	4.58	4.62	4.68	4.62	4.62	4.59
K_t [10^7]	1.55	1.72	1.87	1.96	1.81	1.93	1.67	1.83
Q_{trans} [10^{11}]	2.51	3.07	3.64	3.98	3.42	3.88	2.92	3.49
Q_{HOM1}	6.3E+12	4.5E+12	2.8E+13	6.0E+12	4.3E+12	2.9E+12	2.0E+12	1.4E+12
Q_{HOM2}	6.2E+12	6.5E+13	4.3E+14	1.2E+12	2.5E+12	1.6E+13	6.8E+12	3.6E+14

Module RF calibration measurement is done with LabVIEW test software at 1.3 GHz

$$k_t = \frac{2}{L}\sqrt{\frac{R_{sh}}{Q} Q_L \frac{P_{for}}{P_{trans}}} \times \left[1 - e^{-\frac{\pi f t}{Q_L}}\right], \left[V/\left(m\sqrt{W}\right)\right]$$

$$E_{ACC} = k_t \sqrt{P_{trans}}, \left[V/m\right]$$

Acceptance criteria:

- $Q_{HOM1}, Q_{HOM2} > 1 \times 10^{11}$
- $Q_{HOM1}, Q_{HOM2} > Q_{trans}$

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4.5 CM Cold Test Results

Typical module cold test data in final report (module XM61)

	Name	K_t [10^7]	X- START [MV/m]	BD LIMIT [kW]	BD LIMIT [MV/m]	BD LIMIT Limitation	X - rays [mGy/min] GUN	X - rays [mGy/min] DUMP	Operating Gradient [MV/m]	Operating Gradient Limitation	X- rays 10^{-1} mGy/min [MV/m]
1	CAV00271	1.36	26.1	244.3	31	PWR	1e-3	-	31	PWR	
2	CAV00293	1.45	27.6	230.7	31	PWR	4e-3	-	31	PWR	
3	CAV00298	1.67	20.6	234	31	PWR	1e-3	-	31	PWR	
4	CAV00303	1.74	16.6	242	31	PWR	2.2e-3	-	31	PWR	
5	CAV00309	1.54	-	233.3	31	PWR	-	-	31	PWR	
6	CAV00324	1.81	28.5	221.3	31	PWR	1e-5	-	31	PWR	
7	CAV00323	1.85	30.1	224.9	31	PWR	1.1e-5	-	31	PWR	
8	CAV00915	1.65	24.8	234.9	31	PWR	1e-4	1.2e-5	31	PWR	

Power E_{acc} $\left[\frac{MV}{m}\right]$	Avg P_{forw} [kW]	X-rays $\left[\frac{mGy}{min}\right]$ GUN	X-rays $\left[\frac{mGy}{min}\right]$ DUMP	Comment
23.6	240.1	2.2e-4	2.7e-4	Close-loop
	133.3			without
31	238.9	1.35	0.64	

Power E_{acc} $\left[\frac{MV}{m}\right]$	Avg P_{forw} [kW]	P cryo [W] Σ	Q_0 [10^{10}]
23.6	240.1	5.2	1.25

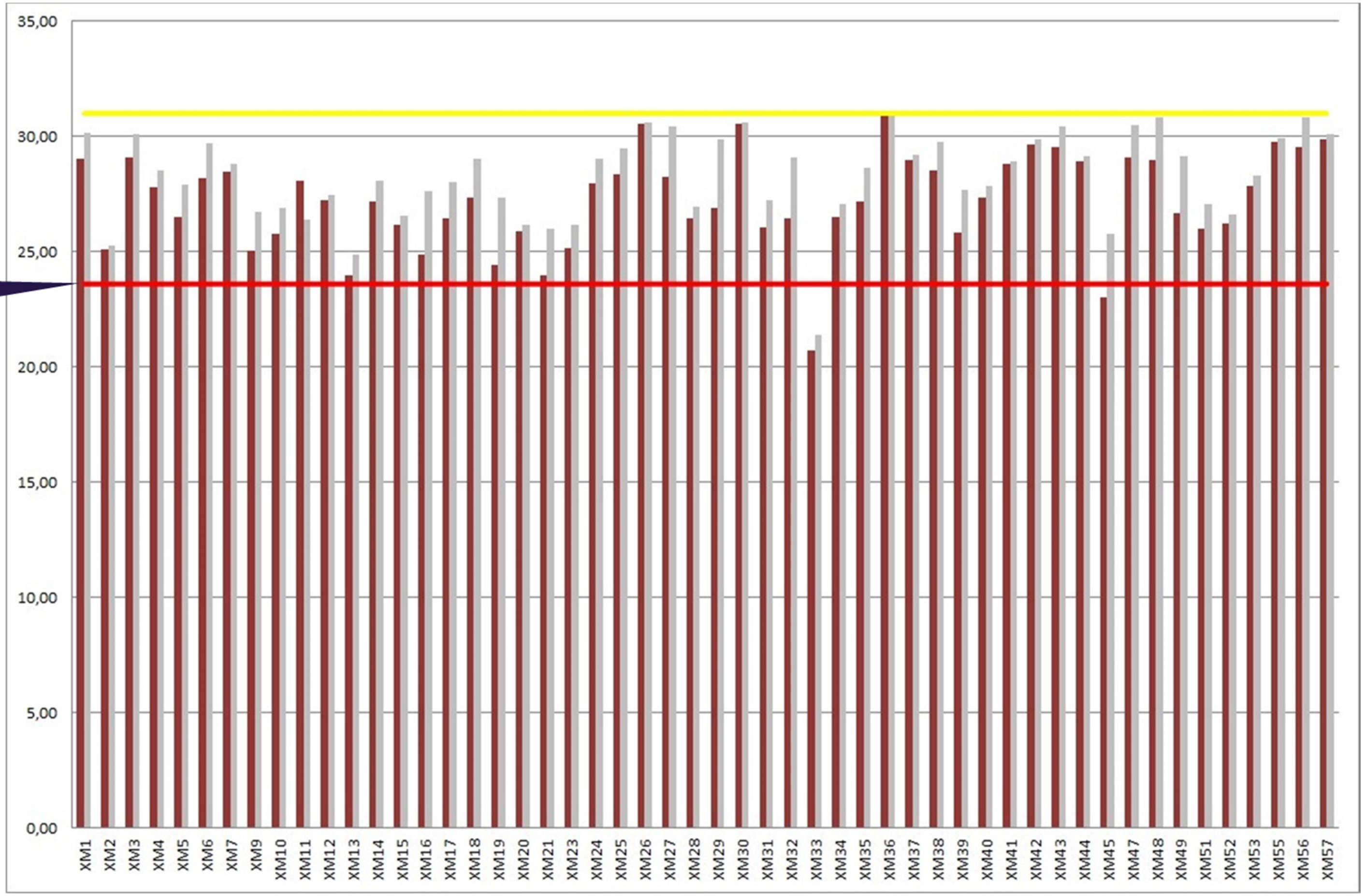
4.6 CM Performance / Gradient

23.6 MV/m

XFEL GOAL

Cavity **operating gradient** in the module is defined as minimum of:

- Quench limit (breakdown) reduced by 0.5 MV/m
- X-ray limit (10^{-2} Gy/min)
- PWR – infrastructure limit equal 31 Mv/m



Averaged maximum (grey) and operating (red) gradients for all tested cryomodules. Yellow line is the power limitation

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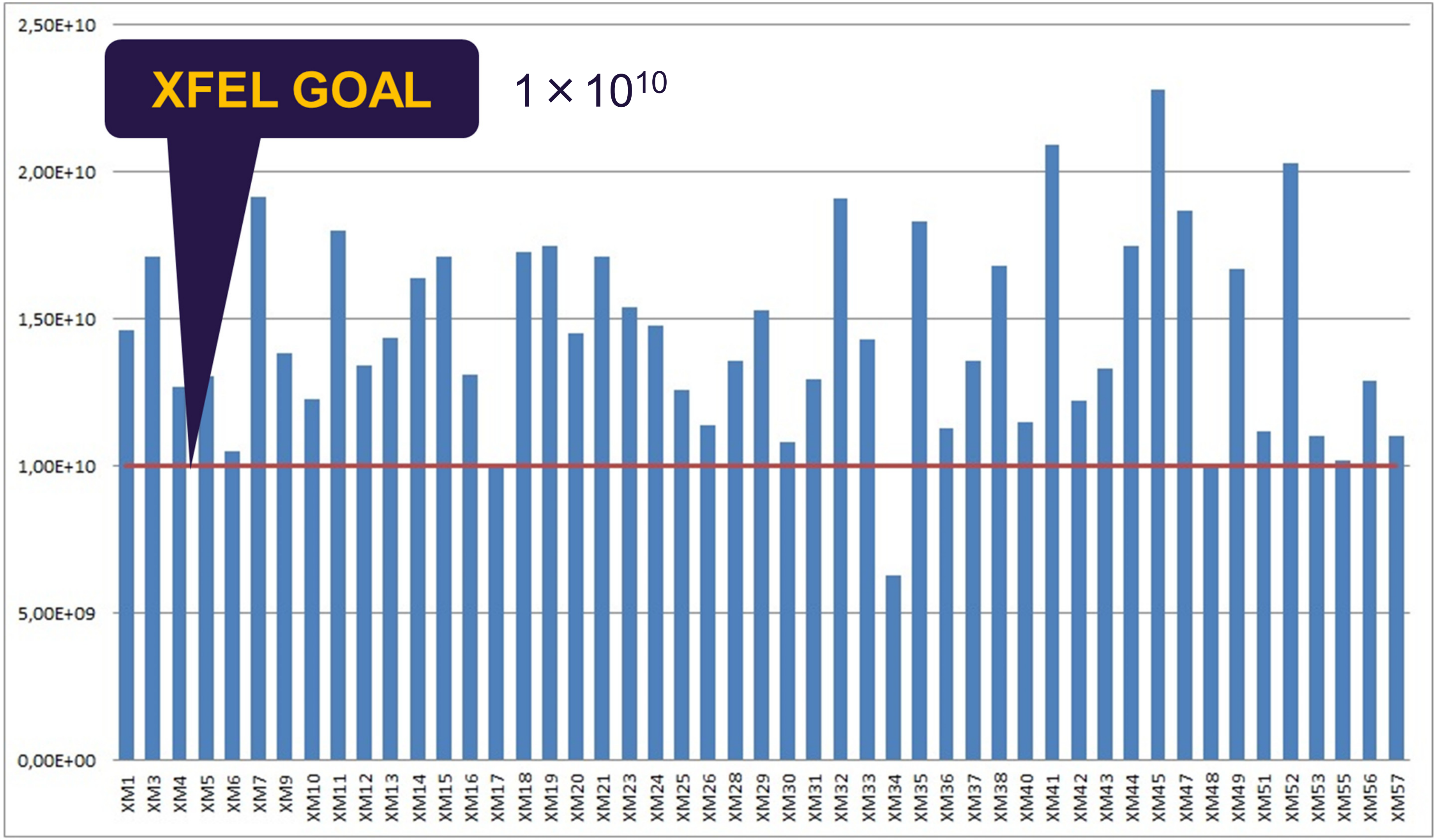
4.7 CM Performance / Quality Factor



Average quality factor for all tested cryomodules.

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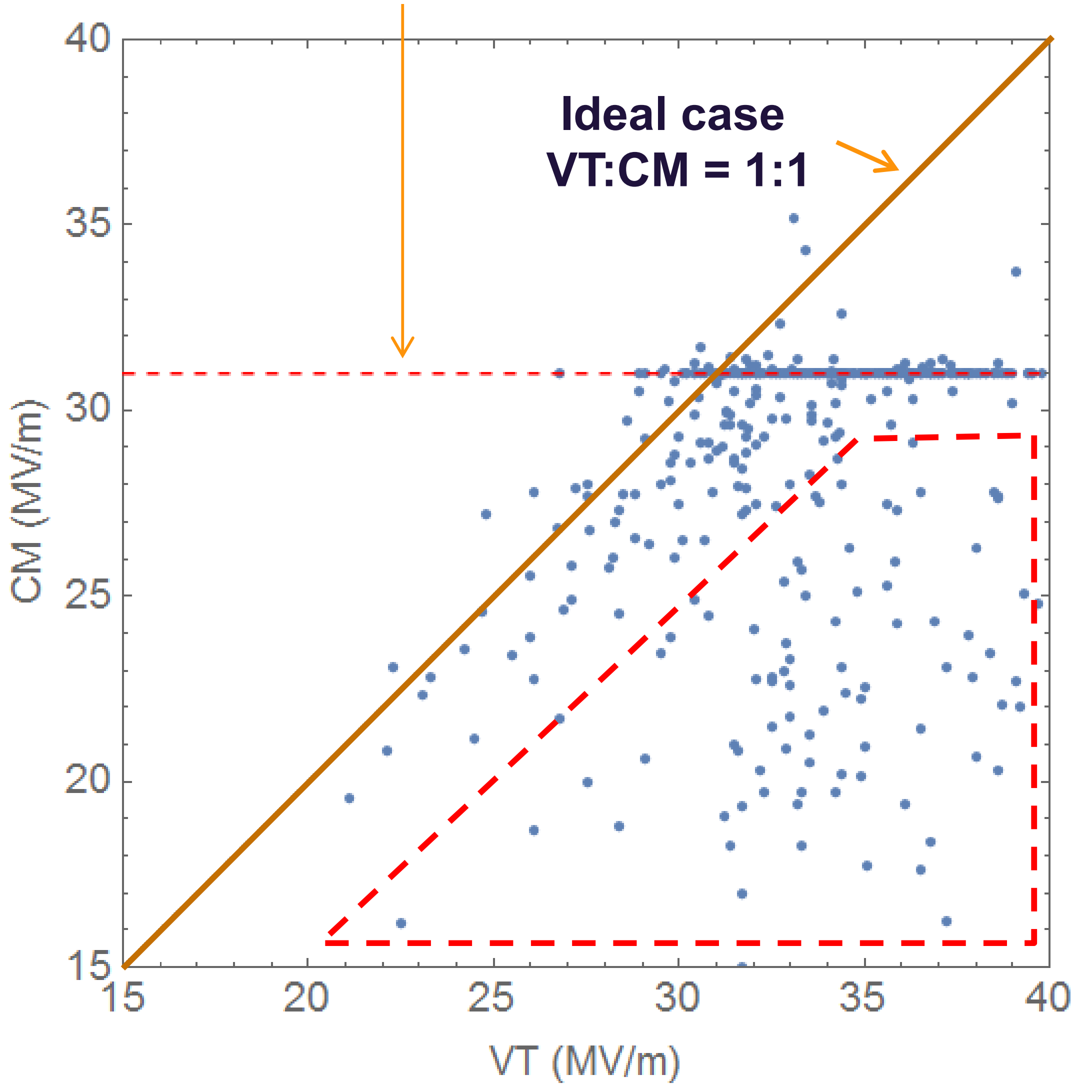
4.8 CM – Vertical Test comparison: max. Gradient

individual cavity comparison

(upper limit due to 31 MV/m limit in module test)



- **we lose between vertical and cryomodule test**
- average VT: (33.8) **30.5 MV/m** (clipped at 31 MV/m)
  average CT: **28.4 MV/m** (includes limit at 31MV/m)

	Vertical test	Cryomodule test
Number of cavities	415	415
Averaged Gradient [MV/m]	28.9	27.2
RMS [MV/m]	2.5	4.6
Min Gradient [MV/m]	20.4	9.2
Max Eacc [MV/m]	31	31

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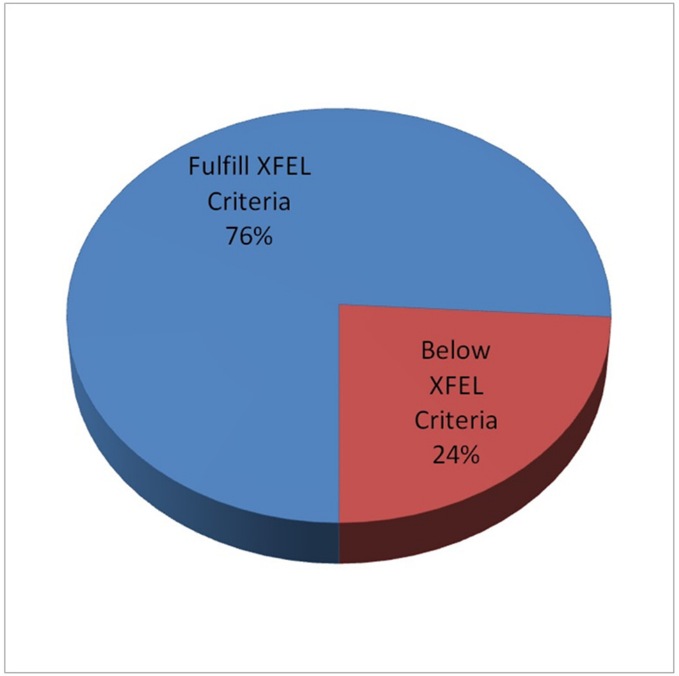
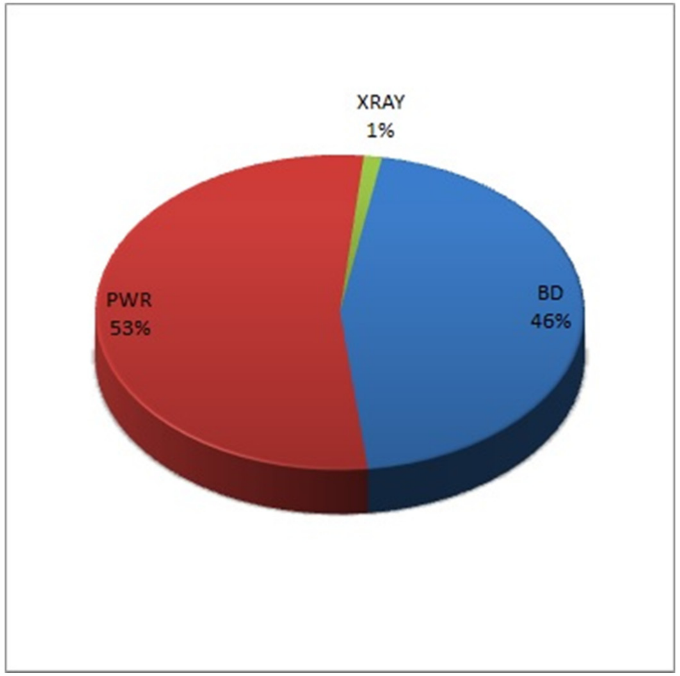
4.9 CM Test Statistics

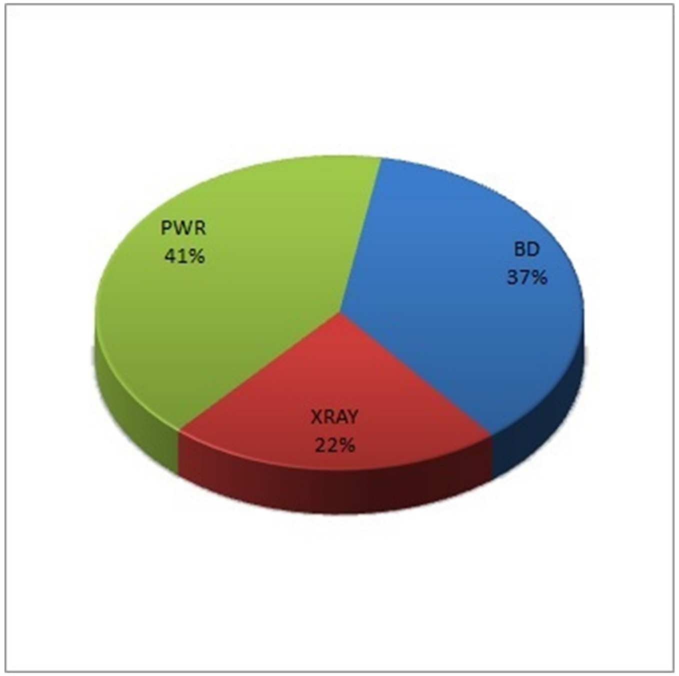
Cavities in cryomodules: statistics



Number of cavities, which do not meet XFEL operating gradient criteria

Limitation for singles cavity maximum accelerating field





Single cavity maximum accelerating field limitation

The average operating gradient for all of the tested cavities is equal to **27.2** MV/m.

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4.10 CM Cryogenic Measurements

Typical cryogenic losses data (module XM64)

area	static	dynamic	total	acceptance
	static	RF 23.6 MV/m	static + total dynamic	static + total dynamic
40/80K	97.96 W	not measured(1)	not measured(1)	125 W
5/8 K	10.93 W	0.55 W(2,3)	11.48 W	16 W
2 K	5.33 W(4)	3.17 W(3)	8.5 W(4)	14 W

(1) Due to short measurement period, it is not possible to reach steady-state equilibrium value, and therefore to determine the dynamic heat load
(2) As RF operation during the dynamic heat load on 2K system was below 4 hours, it is not possible to reach steady-state equilibrium value, and therefore to determine the dynamic heat load
(3) RF power set to 21.7MV/m instead of 23.6MV/m
(4) Static heat loads for Feed-cap and End-cap (1.55 W) are already subtracted

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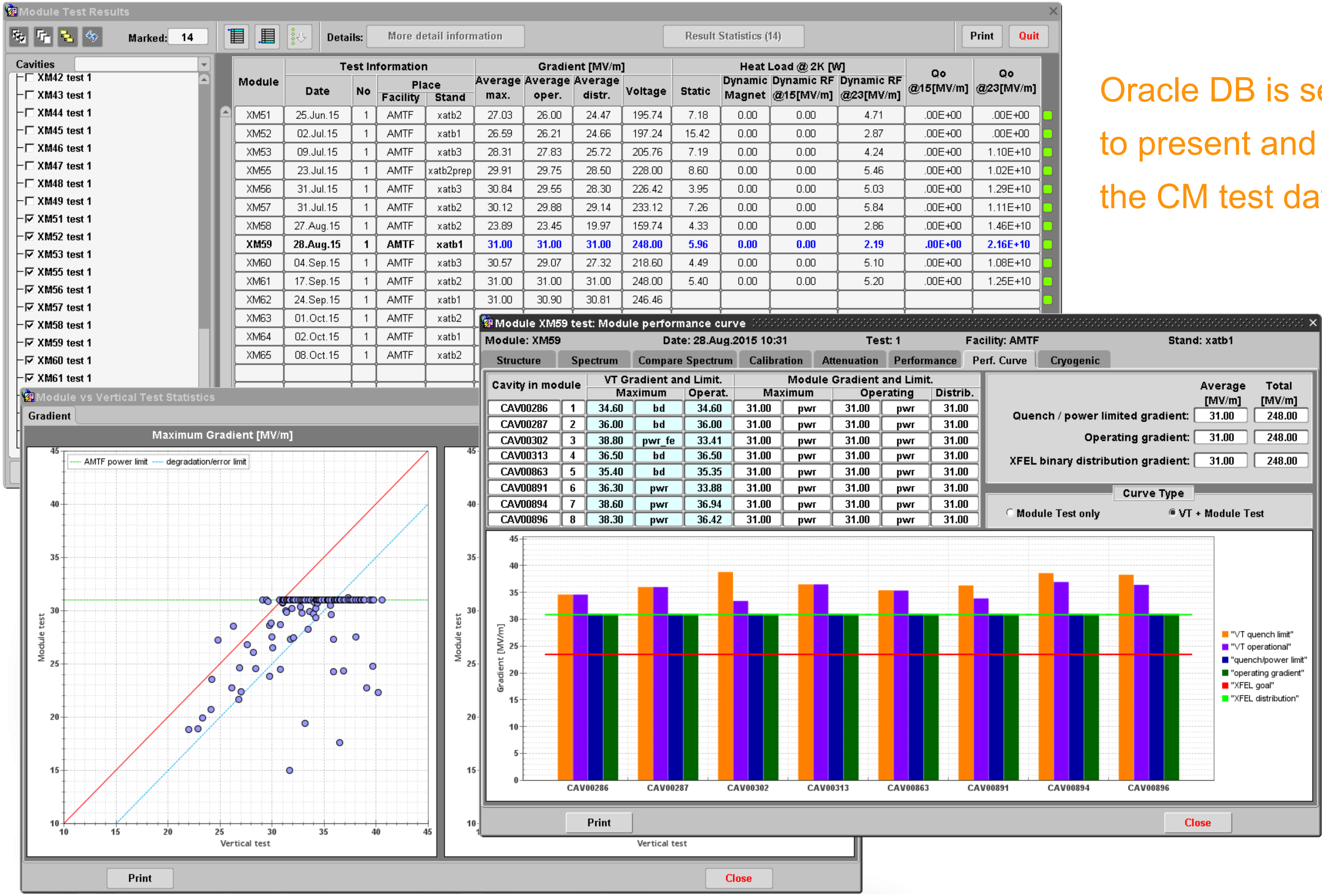
4.11 CM Test Data Base



Oracle DB is set-up to present and analyze the CM test data

V. Gubarev

5. Summary

- E-XFEL CM Test at AMTF@DESY is an important step in CM production. It provides a critical data for later E-XFEL Linac operation as well as multiple CM quality checks.
- Among many important CM Test steps the critical ones are:
  - Warm input RF power coupler conditioning;
  - Vacuum / Cryo-System leak tests at cold (2K);
  - Single cavities performance tests at cold (2K);
  - Auxiliaries (tuners/actuators, magnets etc.) tests at cold (2K);
- Testing the cavities provides the final CM performance data and allows for individual adapted cavity RF power distribution.
- Customized / adapted CM Test Field equipment is critical.
- Customized / adapted CM Test software tools play an important role.
- Taking CM test-stand into operation takes rather long time.
- Optimized and well documented CM Test procedures are critical. CM Test flow and steps are to be adjusted / changed in operation.
- CM Test data storage and analysis are of great importance.