# XFEL cavity production tests and comparison before/after module assembly

**TTC Meeting KEK**
**Dec 2-5, 2014**

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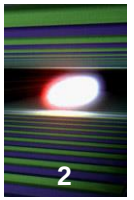
**for the Cavity- and Module Team**

# Outline




- Vertical Acceptance Test
- Module Test
- Changes in Cavity Performance from Vertical Test to Module Test

- More in the “Module Test WG” by Mateusz and Nick

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# Vertical tests at AMTF








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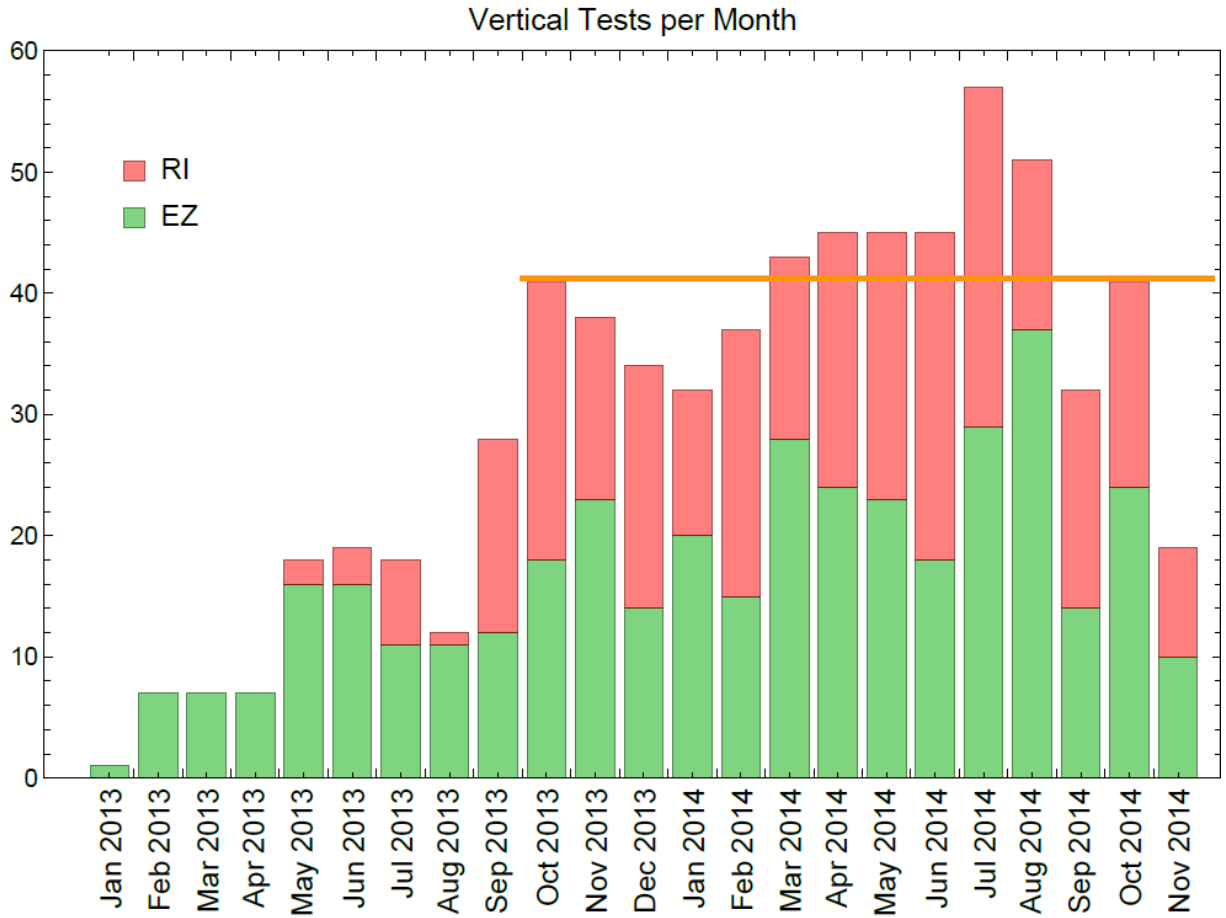
# Number of vertical tests (history)



- **ALL** vertical acceptance tests counted (incl. hall3 + cavities with limited acceptance + return from Saclay + …)




Average:
> **9.5 tests per week**
since Oct 2013

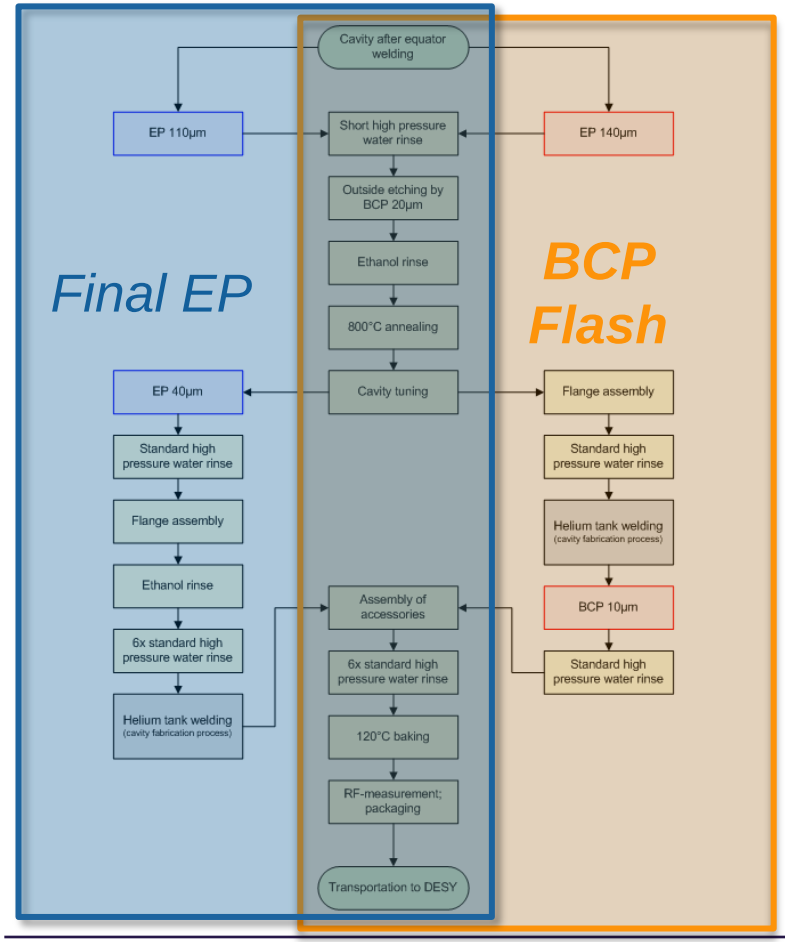
EZ
RI

# Reminder: Cavity Surface Preparation



**Two schemes** for the final surface treatment:

- **E. Zanon:** **Final 10µm BCP** ("BCP Flash")
- **Research Instr.:** **Final 40µm EP**



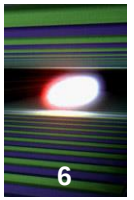

**At both companies all surface preparation infrastructure in full and standard operation!**

Close **supervision** of infrastructure, processes, procedures and handling by DESY + INFN Milano

**No performance guarantee** results in:

- the risk of unexpected low gradient or field emission is with DESY
- responsibility for re-treatment at DESY

# Vertical acceptance tests




- Analysis of vertical acceptance tests includes
  - Series Cavities
  - “HiGrade”-Cavities
  - NO infrastructure commissioning tests

- So far delivered: 512 cavities (Nov 30)
- Total RF tested: ~500 cavities (Nov 30)

- Data analysis group:
  S. Aderhold, L. Monaco, D. Reschke, (D. Sertore), J. Schaffran, L. Steder, N. Walker, K. Yamamoto
  + XFEL cavity data base team: V. Gubarev, D. Gall, S. Yaser
- Analysis fully based on XFEL cavity data base

- Status of vertical tests analysis: **Nov 10, 2014** (~470 cavities)

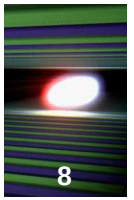
# RF test conditions


- **Cavity "full equipped" refers to**
  - Dressed with He-tank (except of "HiGrade" cavities)
  - Equipped with fixed High Q-antenna, Pick-up and two HOM-antennas

- Only Q(E)-measurement at 2K + fundamental mode frequencies
  - Remark: no $Q_0(T)$,
    no $Q_0(E_{acc})$ in fundamental modes,
    no $Q_0(E_{acc})$ at various bath temperatures
  - All cavities checked for Q-disease by parking at 100K

- Measurement with fix coupling
  => over-coupled at low and medium gradients
  => error impacted by $\beta > 1$ coupling
- "Long pulse" operation (few seconds RF on); not full cw
  (in order to protect HOM feed-throughs)
- Up to now no administrative radiation limit

# Acceptance Criteria for Vertical Test





- **Acceptance criteria:**
  "Usable gradient"
  - INITIAL: >26 MV/m (10% margin to required average design operating gradient)
  - NEW (after analysis of retreatment results in May 2014):
    **> 20 MV/m** (for optimized number of retreatments and retests)

- **Definition of usable gradient:**
  - Gradient of Quench or
  - Gradient at Unloaded $Q_0 < 1x10^{10}$ or
  - Gradient at X-ray level:
    upper detector > $1x10^{-2}$ mGy/min; lower detector > 0.12 mGy/min
    (different location/distance of detectors)

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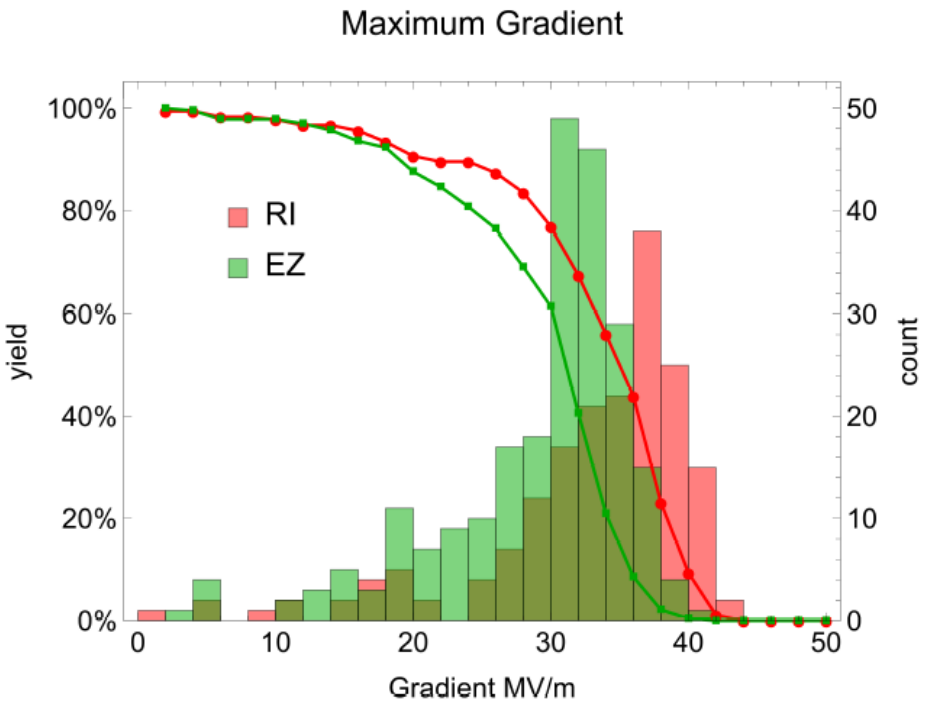
# Results: Maximum Gradient "As received"



- Analysis: No selection done, no cut




| | RI | EZ | Total |
|---|---|---|---|
| Tests | 182 | 234 | 416 |
| $G_{AVG}$ (MV/m) | 32.9 | 29.1 | 30.8 |
| $G_{RMS}$ (MV/m) | 7.6 | 7. | 7.5 |
| yield @ 20MV/m | 91% | 88% | 89% |
| yield @ 26MV/m | 87% | 76% | 81% |
| yield @ 28MV/m | 84% | 69% | 75% |

- Reminder: RI applies "Final EP" => higher gradients expected

- Comment: "Missing" cavities with status "as received"?
  => About 50 cavities sent back to vendor (new status "retreatment at vendor")



***Preliminary data; results are not published***

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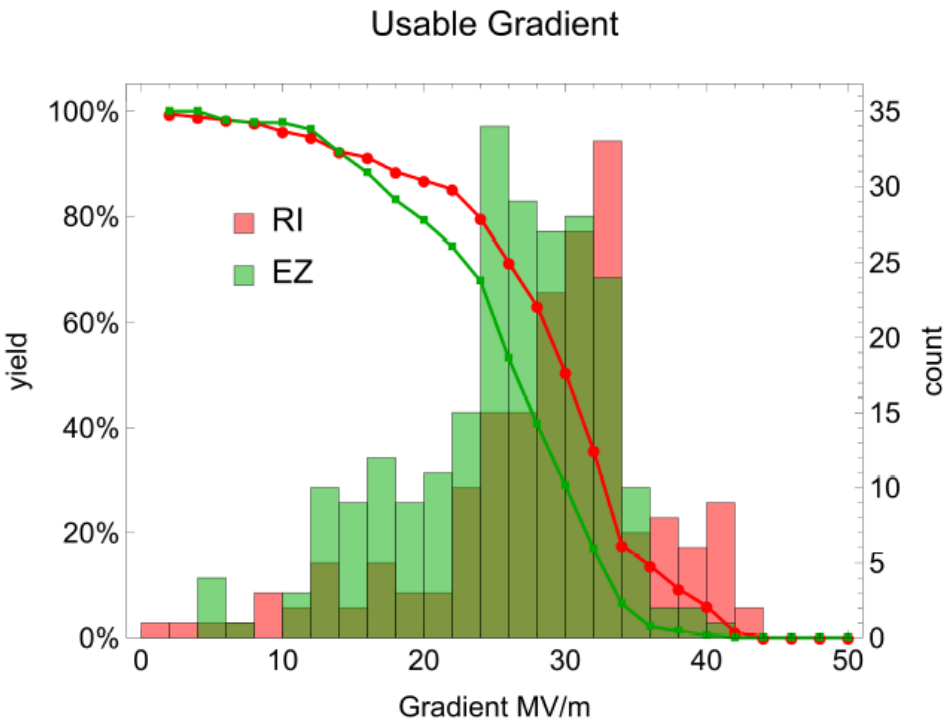
# Results: Usable Gradient "As received"



- Usable Gradient:




| | RI | EZ | Total |
|---|---|---|---|
| Tests | 182 | 231 | 413 |
| $G_{AVG}$ (MV/m) | 28.6 | 25.5 | 26.9 |
| $G_{RMS}$ (MV/m) | 7.9 | 6.9 | 7.5 |
| yield @ 20MV/m | 87% | 79% | 83% |
| yield @ 26MV/m | 71% | 53% | 61% |
| yield @ 28MV/m | 63% | 41% | 51% |

- "not passed":
  - re-treatment at DESY; partly still to be done
  - "special" handling e.g. retreatment by vendor accepted



*Preliminary data; results are not published*

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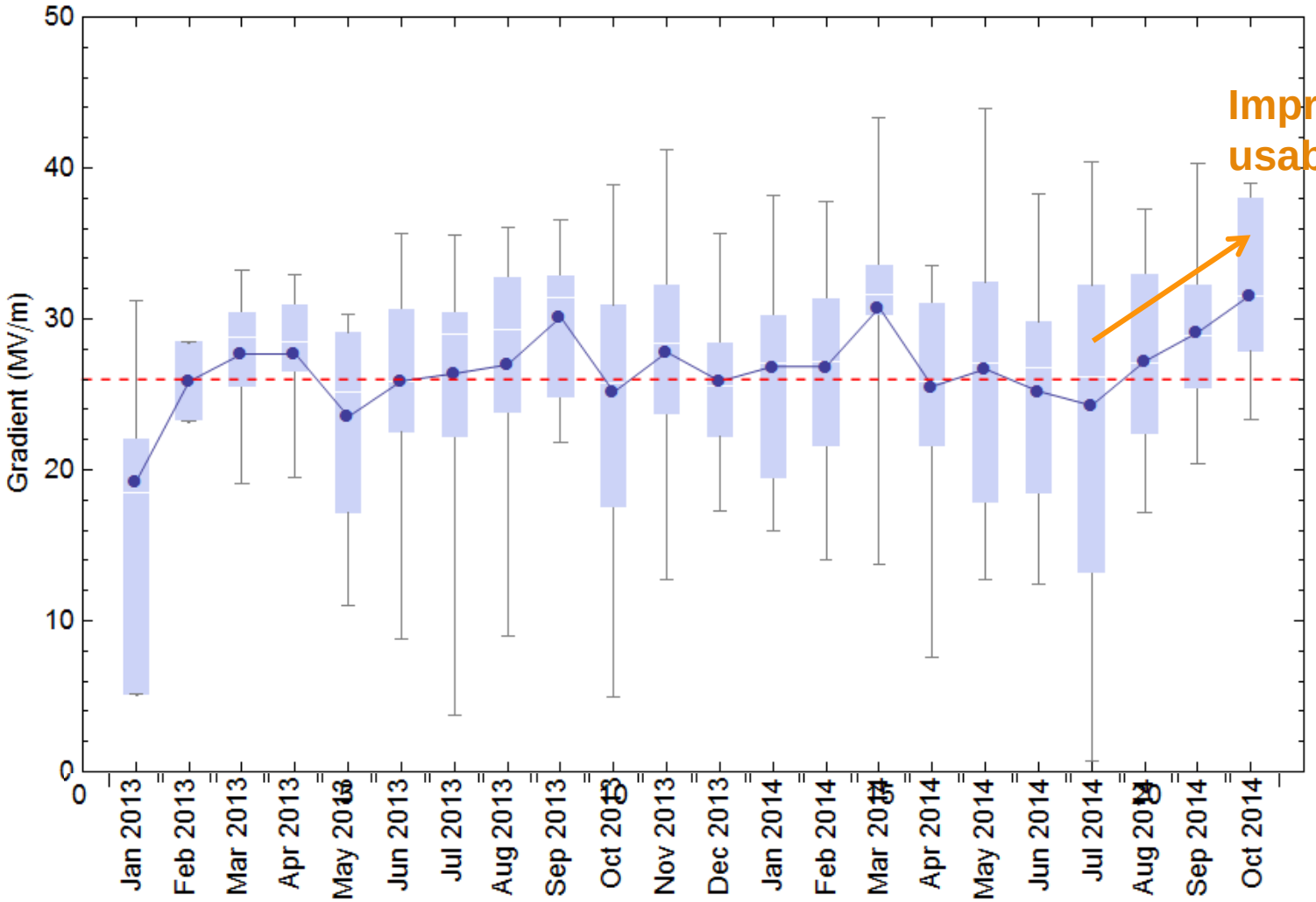
# Results: Trend of Usable Gradient “As received”



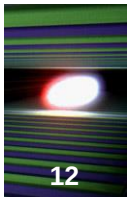



**Improvement of usable gradient?**



***Preliminary data; results are not published***

# Impact of Re-Treatment




- Analysis of ~80 cavities after **first** re-treatment => **typically HPR**
- Pairs of vertical tests of same cavity taken => before vs. after RT

- Reasons for re-treatment:
  - mostly **field emission** (61 cavities)
  - quench at “low” gradient (7 cavities)
  - low Q-value at low gradient (6 cavities)
  - leak (2 cavities)
  - other (6 cavities)
- Remark:
  - Higher priority on curing “field emission”, “low Q”, …
  - Quench gradient > 20 MV/m (often) accepted also for initial acceptance criteria
- Improved performance in the last months => to be confirmed

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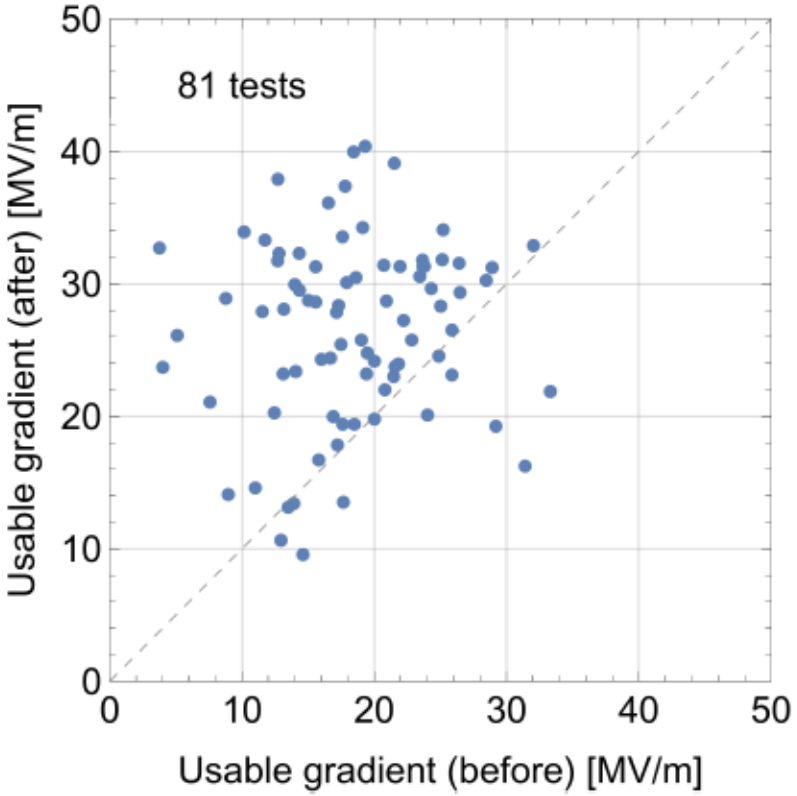
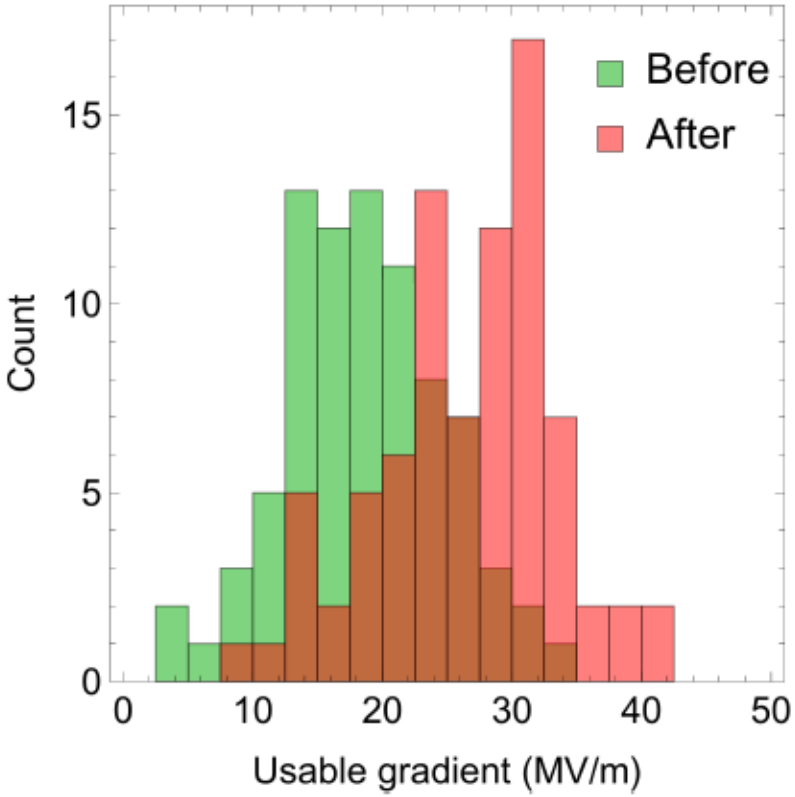
# Re-Treatment: Gradients






| | Before | After |
|---|---|---|
| Tests | 81 | 82 |
| $G_{AVG}$ (MV/m) | 18.5 | 26.6 |
| $G_{RMS}$ (MV/m) | 6.3 | 6.8 |
| yield @ 20MV/m | 40% | 83% |
| yield @ 26MV/m | 10% | 56% |
| yield @ 28MV/m | 7% | 50% |



***Preliminary data; results are not published***

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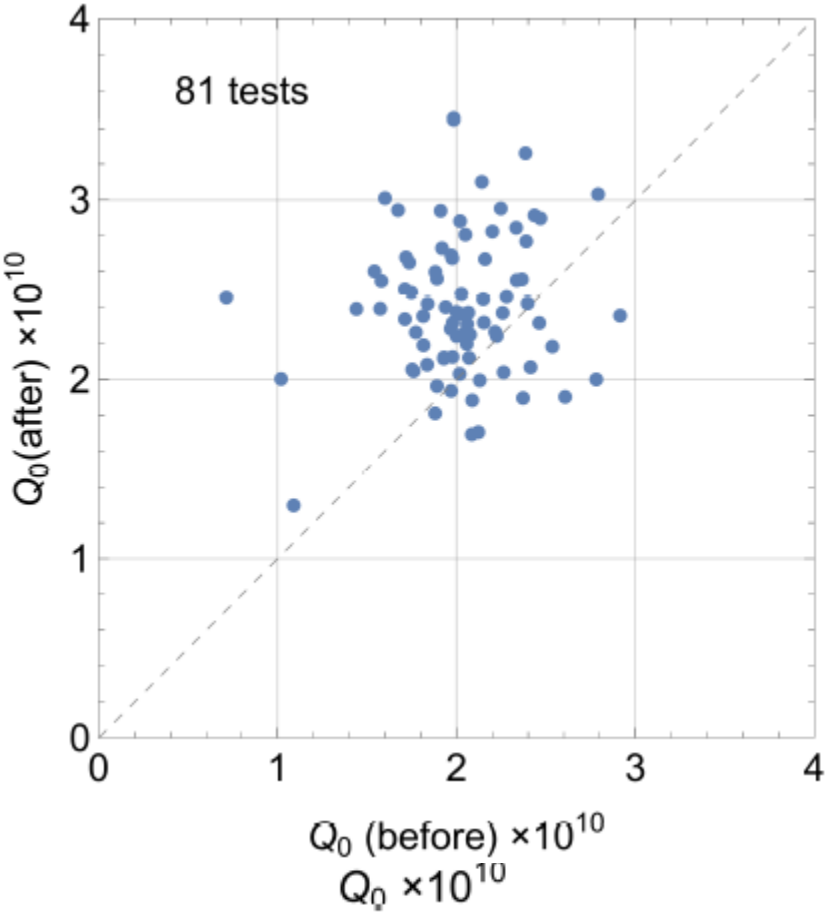
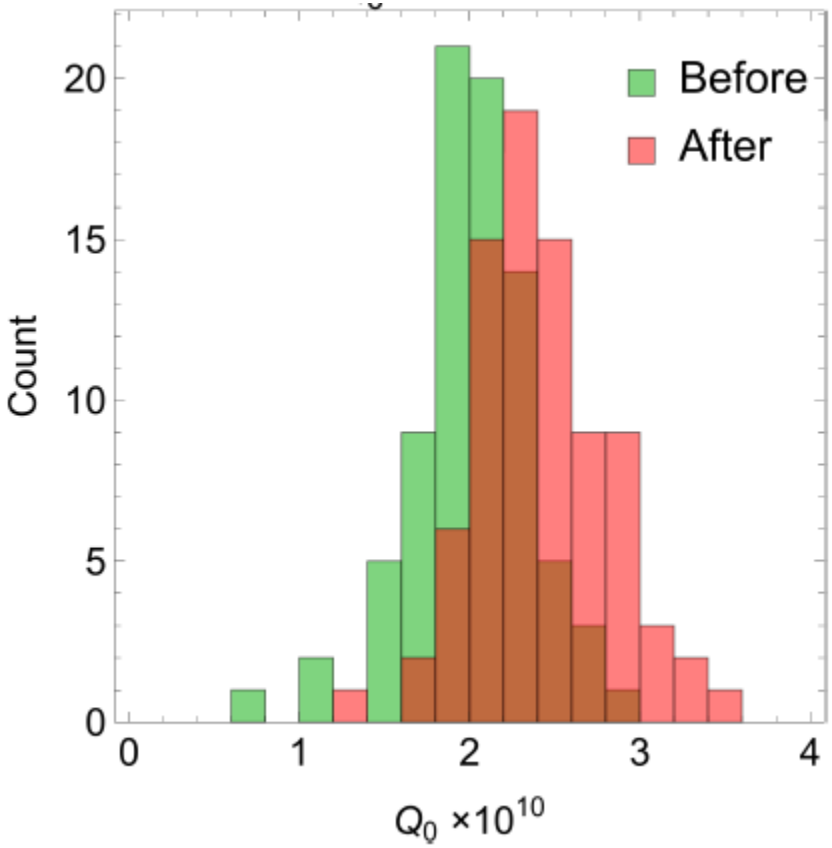
# Re-Treatment: Q-Value at 4 MV/m






| | avg | rms | SE |
|---|---|---|---|
| before | 2.02 | 0.36 | 0.04 |
| after | 2.4 | 0.38 | 0.04 |

Remark: Trend of Q-values stable over production time



***Preliminary data; results are not published***

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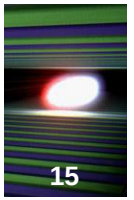
# Other cavity related “challenges”

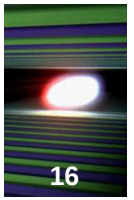



- He-Tanks: One critical dimension NOT well-defined in DESY drawings
  => not all positions in module possible
  => solved: cavities shortened by 1mm + “sorting” wrt. position in module
- 2-phase line (longitudinal weld) does not fulfill PED-requirement
  => solved, but significant effort; 2-phase lines on affected cavities + He-tanks exchanged
- Q-values of critical HOM out of expected range (several cavities):
  => reason still under investigation
- Scratches by wrong tooling + EP electrode at iris (several cavities)
  => solved: identified with high resolution optical inspection + fixed for future cavities (affected cavities require rework procedure!)
- Splatters (+holes) during equator welding (several cavities)
  => instable parameters of EB-machine; rework procedures in application/preparation
- 3D- Transfer measurement (reference for string alignment) incorrect
  => solved?: improper measurement procedure identified



***Preliminary data; results are not published***

# Other cavity related “challenges” II




- “Special” (physically challenged) cavities at both vendors (several cavities)
  => individual time consuming rework procedures
- Suspicions of cold leaks
  => still open; very often not confirmed at 300K + in re-test after reconnection
- Post-Documentation batch of first series cavities + “special” non-conform cavities
  => work will be finished end of 2014/beginning of 2015



***Preliminary data; results are not published***

# Vertical test => string assembly



- **Sorting of cavities for string assembly** according to
  - gradient
  - mechanical constraints

  => **string proposal**
- routine weekly transport in boxes to Saclay => very reliable, but shock log data still not fully understood
- **Cavities up to XM31 at Saclay**

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# Module Test at AMTF



- 22 modules arrived with 13 modules tested (XM-3 excluded)
- 3 horizontal test stands in full operation

# Module Test Procedure

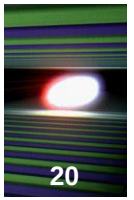


- **Detailed test procedures** described in detail at last TTC Meeting + by Mateusz Wiencek in WG
- Relevant for cavity performance:
  - **Flat-top** measurements of **individual** cavities
  => **gradient** + x-ray values
  - **Heat load** measurement at 15 MV/m + 23.6 MV/m of **all** cavities
  => **average Q-value** + x-ray values

- **In-situ Processing** done in 1. Flat-top measurement (followed by 2. FT-measurement for confirmation)
  if necessary: add. **processing with short pulses** (750µs + 100µs)

- **Diagnostics** at Module Test Stand
  - Quench detection system
  - Two x-ray detectors at each end of the module
  (- dark current monitors => still under commissioning)

# Figure of Merits of Module Test





- **Maximum Gradient** given by:
  - quench limit
  - rf power limit at ~31 MV/m
  (- x-rays)

- **Operational Gradient** defined by:
  - quench limit – 0.5 MV/m
  - rf power limit at ~31 MV/m
  - x-ray limit of $10^{-2}$ mGy/min (at one detector)

- No Q-value measured for individual cavities!

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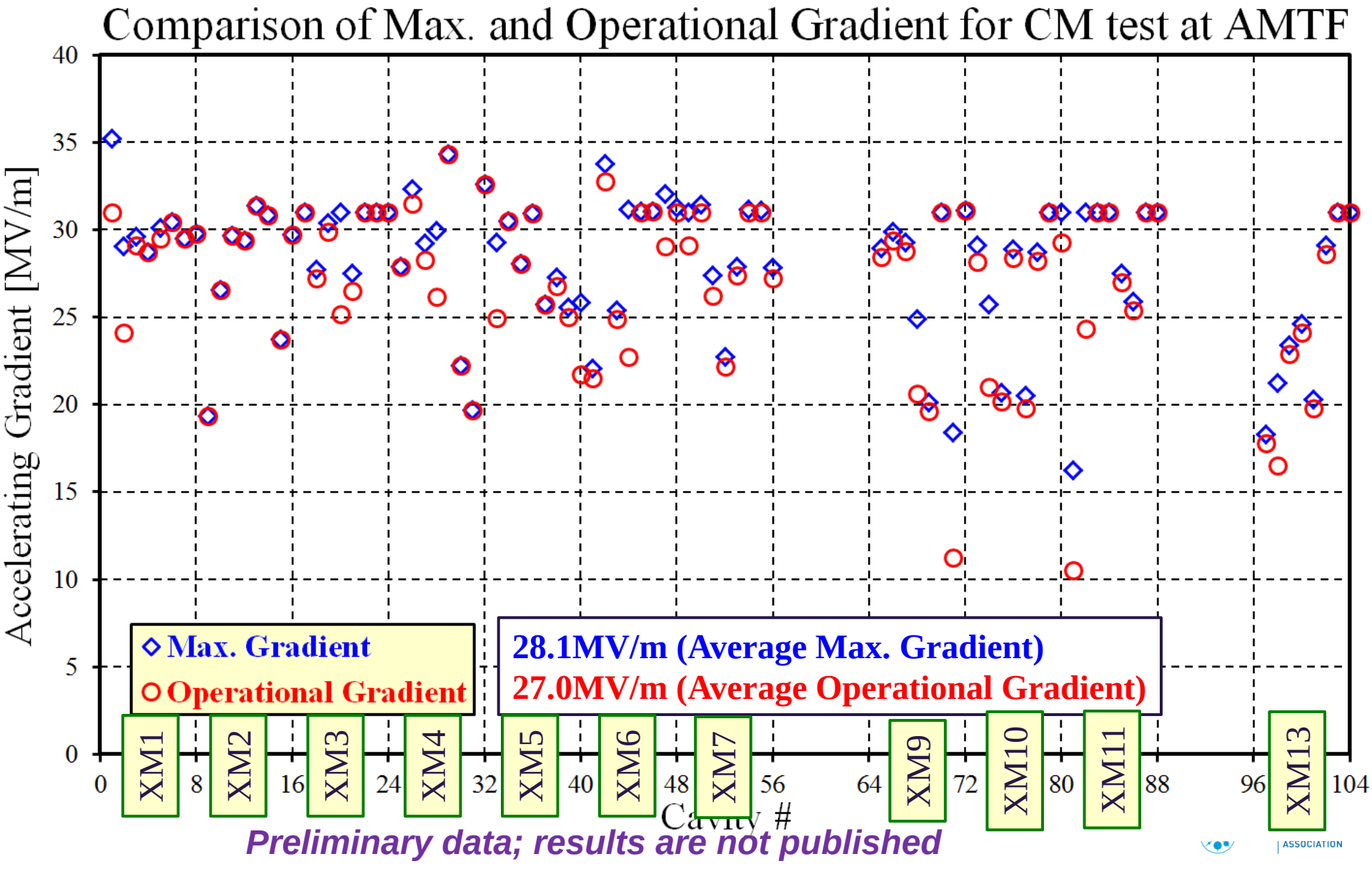
# Module Test Results

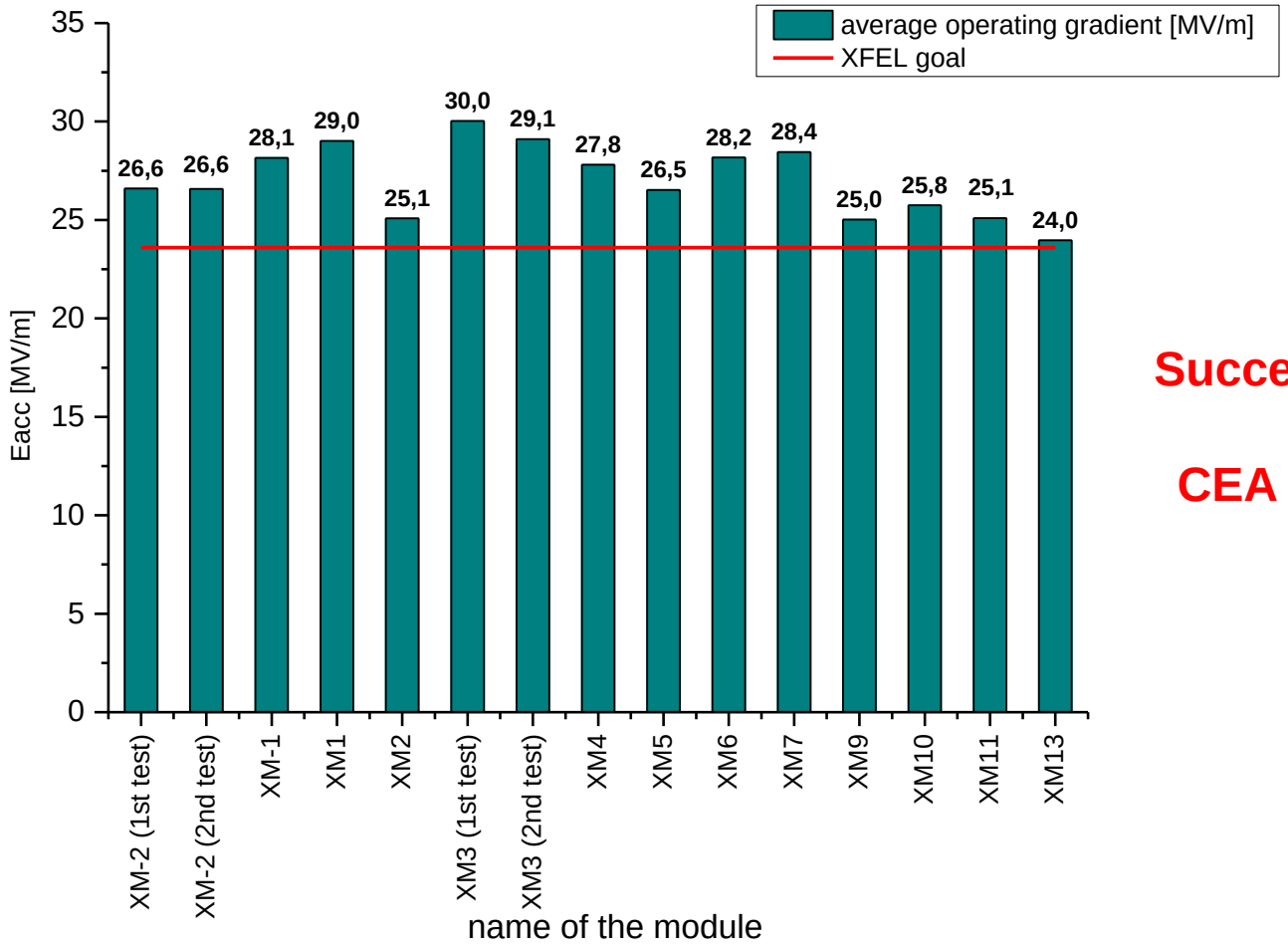




# Module Test Results II



- **Average Operational gradients** of modules with individual rf distribution
- **All modules can be operated above 23.6 MV/m !!**




**Successful technology transfer to CEA Saclay + Alsyom**



*Preliminary data; results are not published*

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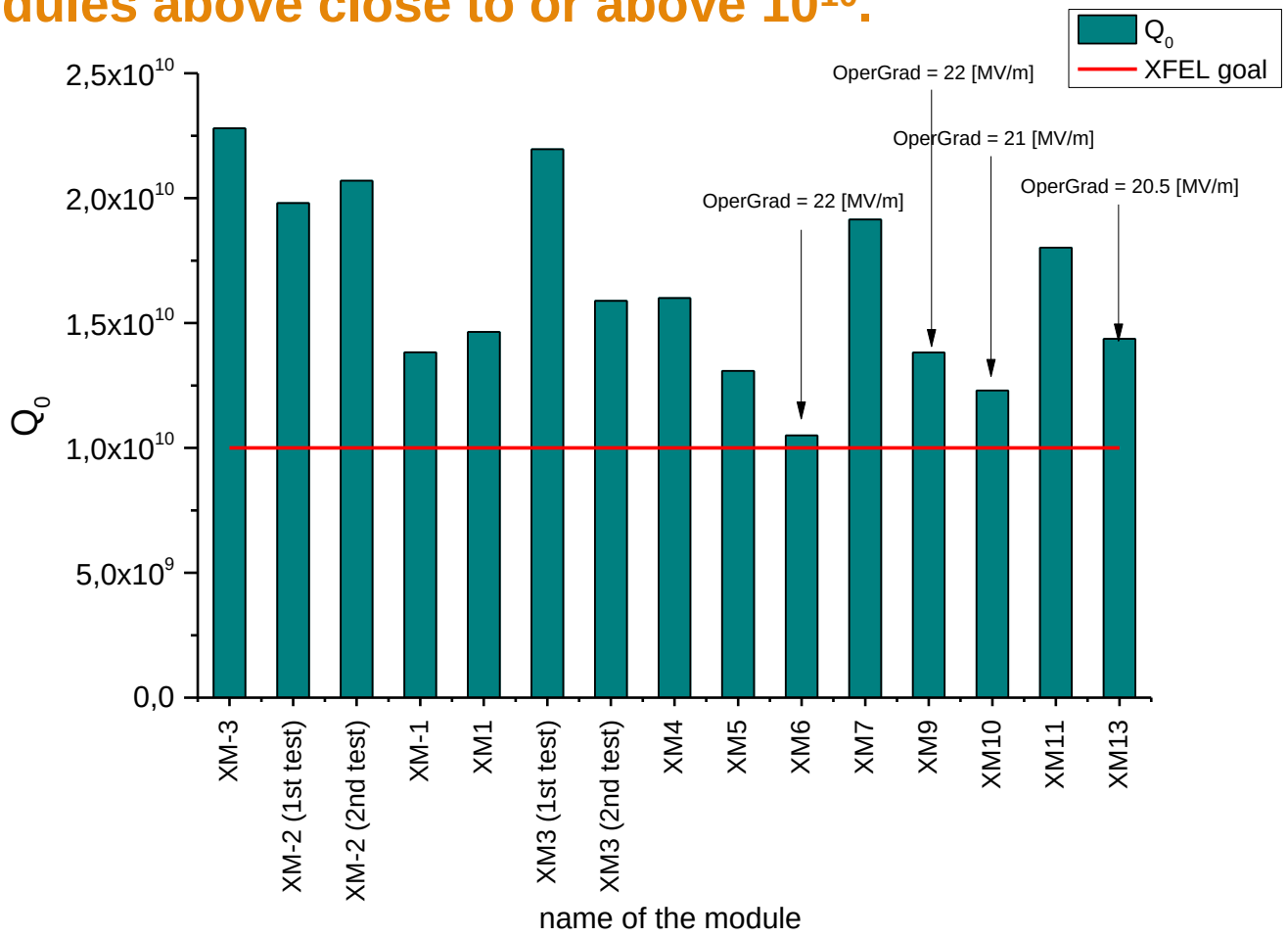
# Module Test Results III



- **Averaged Q-values at 23.6 MV/m** of modules from heat load measurement (in case of cavities with lower gradients => reduced average gradient)
- **All modules above close to or above $10^{10}$.**



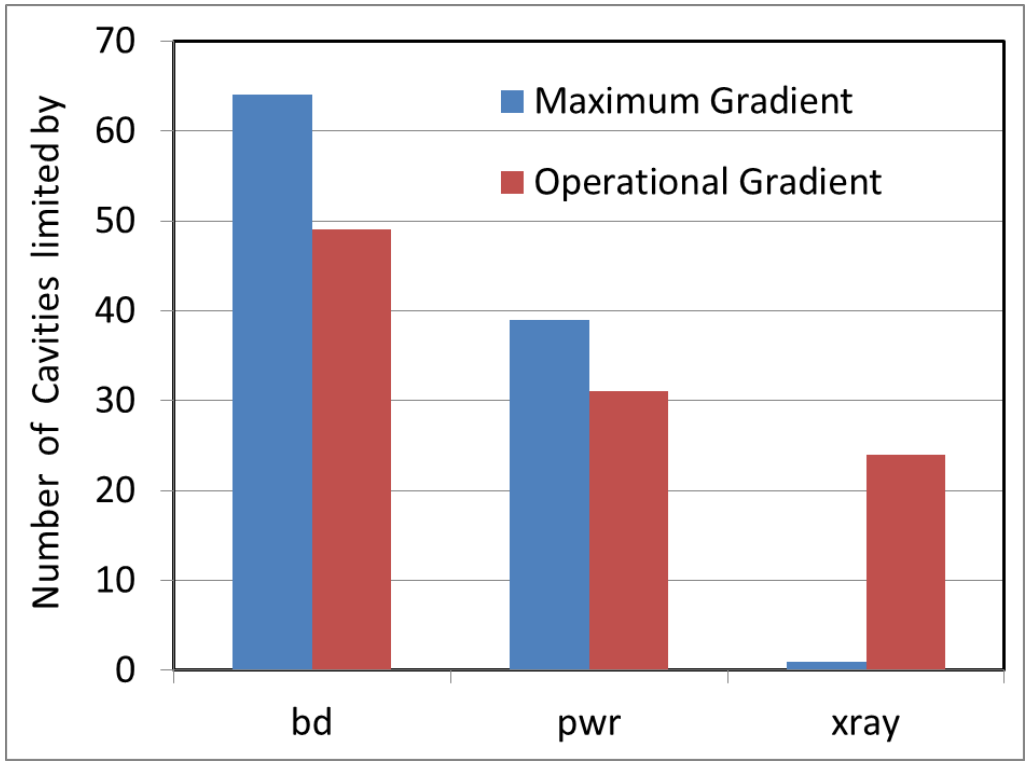



*Preliminary data; results are not published*

# Module Test Results: Limitations



- No hard Multipacting barriers => fast processing (if any; <1h per cavity)
- Limitations of Maximum + Operational gradient (XM-2 to XM13: 13 modules, 104 cavities):





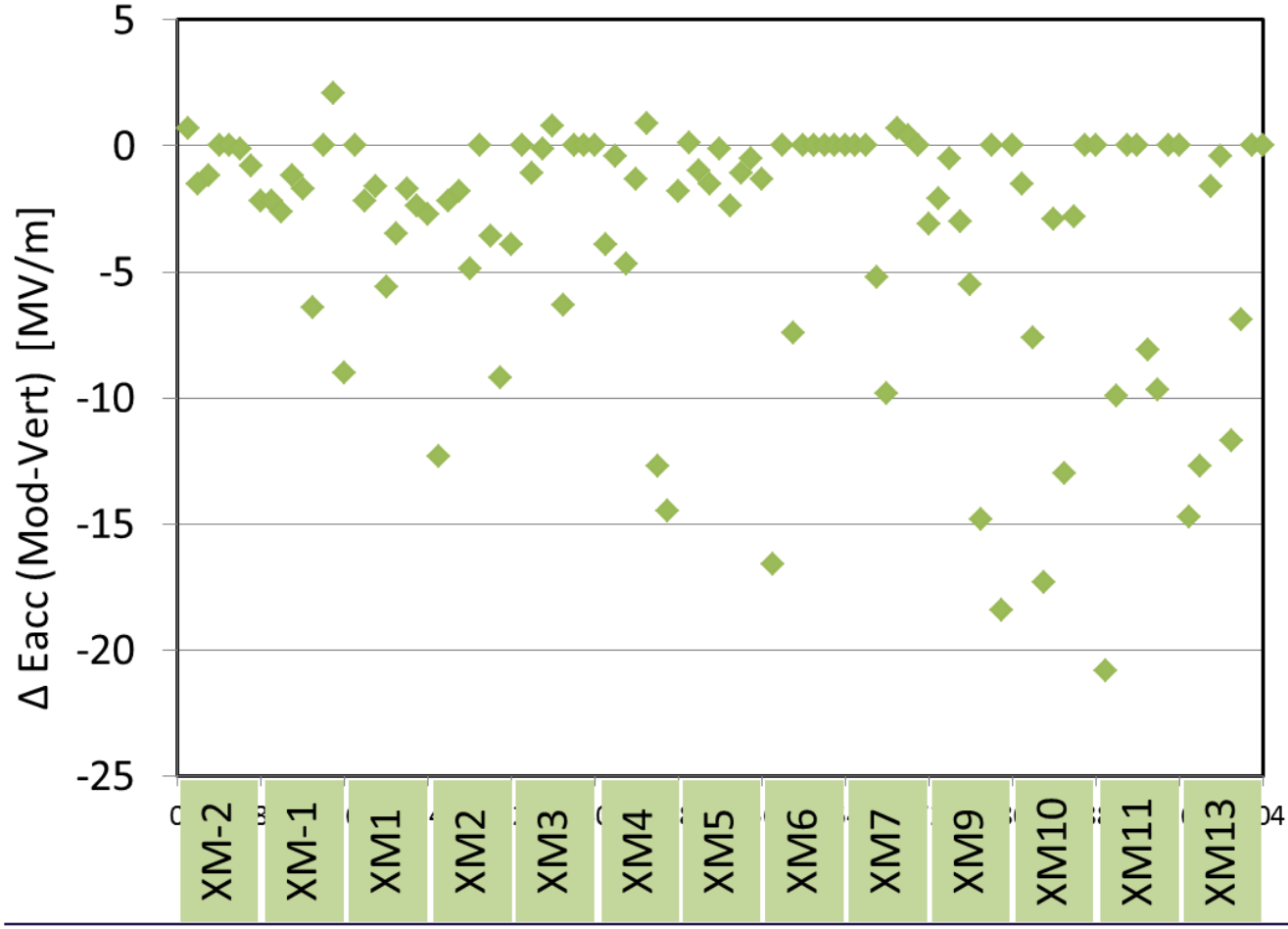

*Preliminary data; results are not published*

# Changes in Cavity Performance from Vertical Test to Module Test



- Hans: “too often we are disappointed by a decreased gradient of single cavities”
- **Difference of maximum gradient from module test and vertical test**

ΔEacc(Mod-Vert) vs. Module

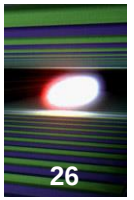



Remark:
If Module Test is limited by available RF power (~ 31 MV/m)
**=> Ignore the decrease of maximum gradient**
(set ΔEacc = 0)



*Preliminary data; results are not published*

# Changes in Cavity Performance from Vertical Test to Module Test




- Decreased performance has been observed after module assembly at DESY (FLASH modules), Fermilab (CM-1), KEK (S1-global), Saclay (XFEL modules)
  => not site dependent
  => typically 0 – 3 cavities affected
  => more **quench**, than field emission limited (see below)
  (- enhanced field emission => typically explained by particle contamination during handling or improper venting condition
  - **reduced Quench gradient =>???**)

- Discussions and presentations at TTC Meetings (e.g. Beijing 2011 + Saclay Nov 2014), SRF 11, …

- Intensive analysis was done for (at least) FLASH modules (presented at TTC Dec 2011)
  => see below

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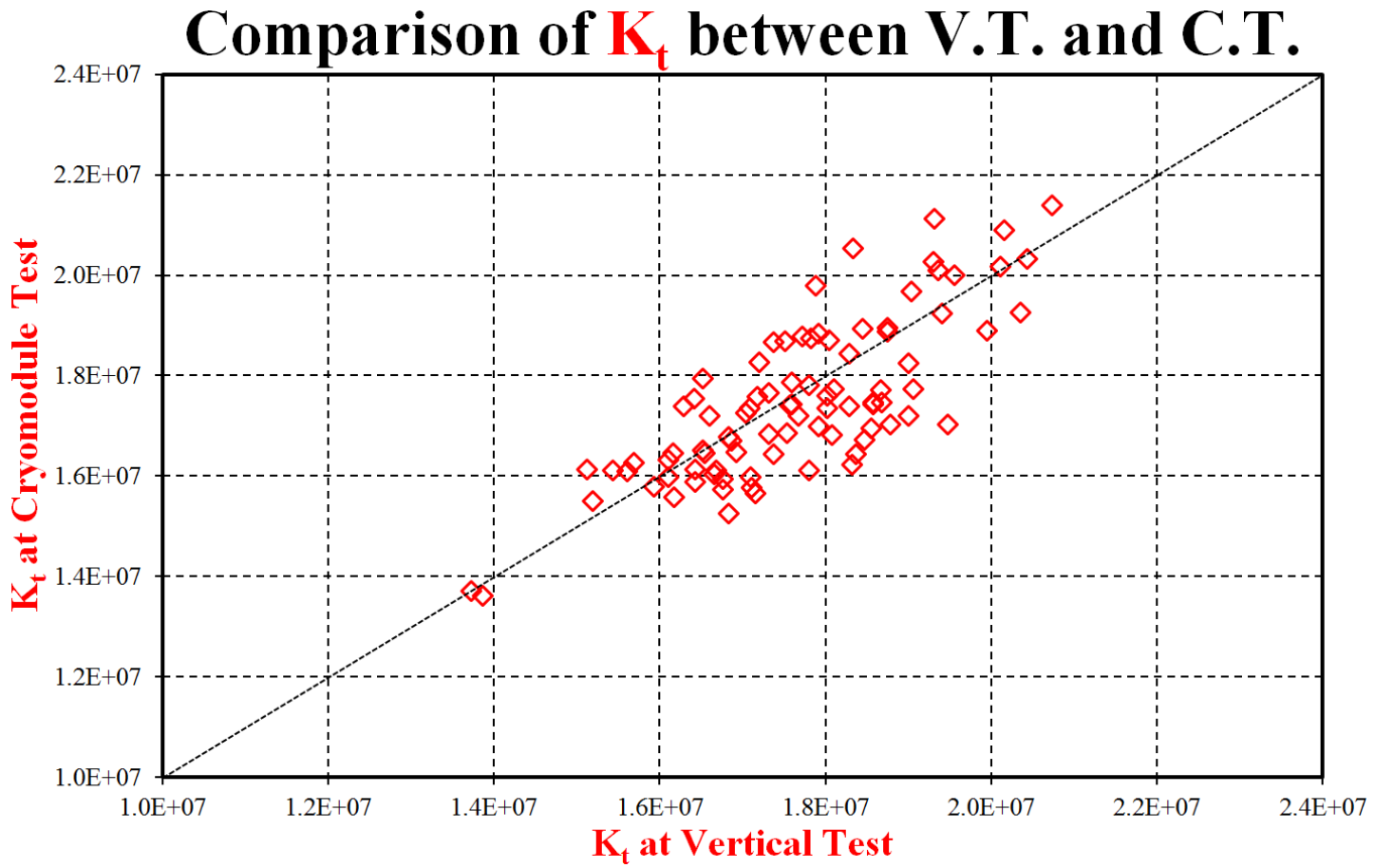
# Comparison of field calibration constant $k_t$



- Crucial is correct calibration of field calibration constant: $k_t$
  => $E_{acc} = k_t \cdot \sqrt{P_{trans}}$
- Error of ~10% possible => not sufficient to explain decrease of gradient






*Preliminary data; results are not published*

# Comparison of gradients: vert vs. hor



- **What gradient to compare?**
  - different rf power limits
  - different x-ray measurement arrangement (see D. Kostin, SRF 2011)
  - pulsed vs. “nearly cw” operation
  - Q-value cannot be measured for individual cavities in module test

  => Given “usable gradient” of vertical test and “operational gradient” of module test **cannot** be compared simply 1:1

- **Quench** is clear cavity limitation => **ok**
  (but pulse operation may lead to little higher quench gradient by shifting the thermal limit)
- **X-ray** limitation is less exact
  e.g. XM13, C7+8 with a x-ray limitation of “usable gradient” in vertical test at ~25 MV/m do **not** show significant x-rays in module test up to 31 MV/m
  => nevertheless significantly decreased performance is detectable
- **Q-value** important for heat load of accelerator, but not to measure for individual cavities in module test => ??



*Preliminary data; results are not published*

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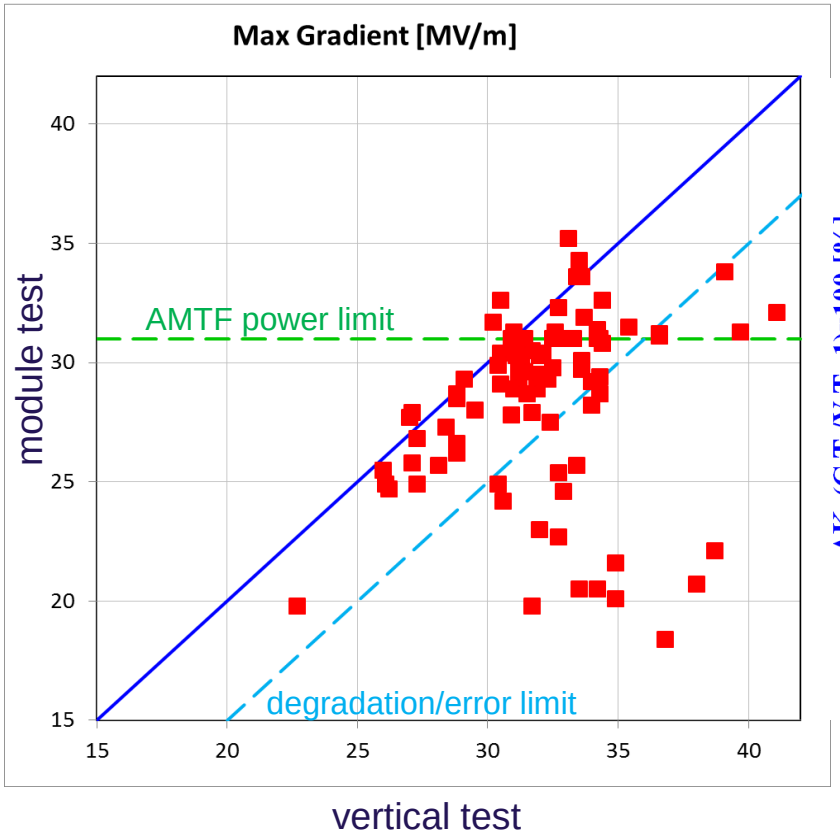
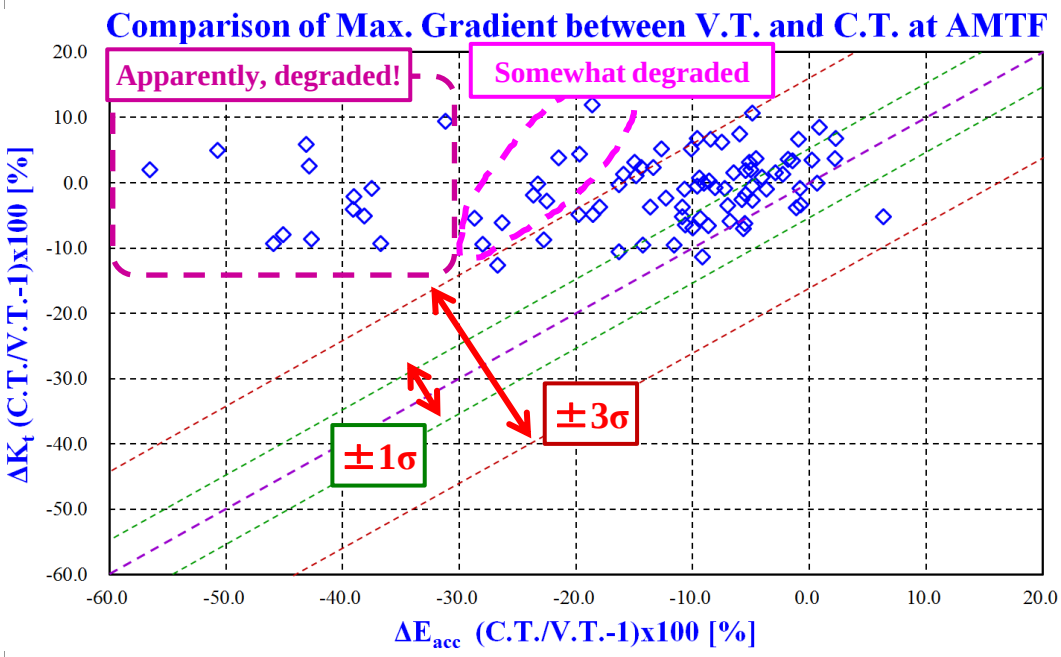
# Observations



- Cavities with decreased gradient performance in XFEL-modules
- No dependence on $k_t$
- Critical decrease to operational gradient in a module less than 25 MV/m happened to 17 cavities, or 19% (out of 88 cavities)



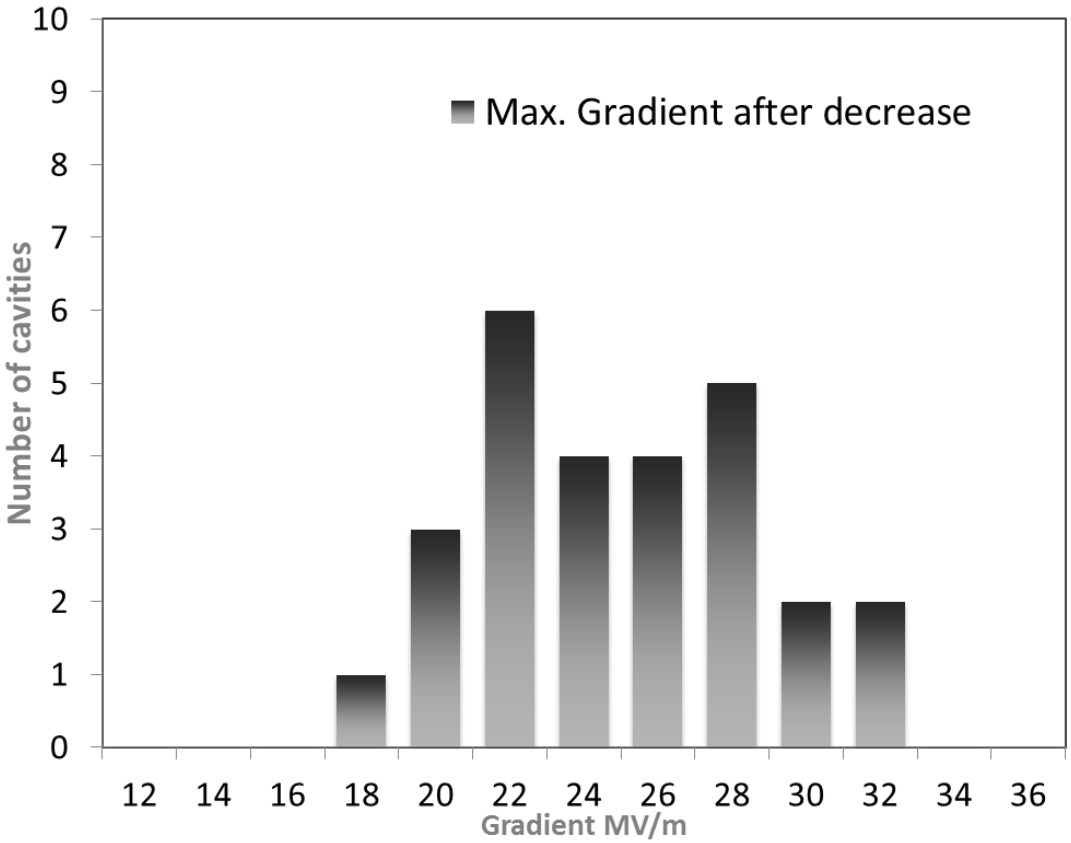



*Preliminary data; results are not published*

# Observations: Gradient distribution



- Decreased maximum gradient:
  - nearly all cavities limited by quench
  - distribution of gradients: not always limited around 20 MV/m!



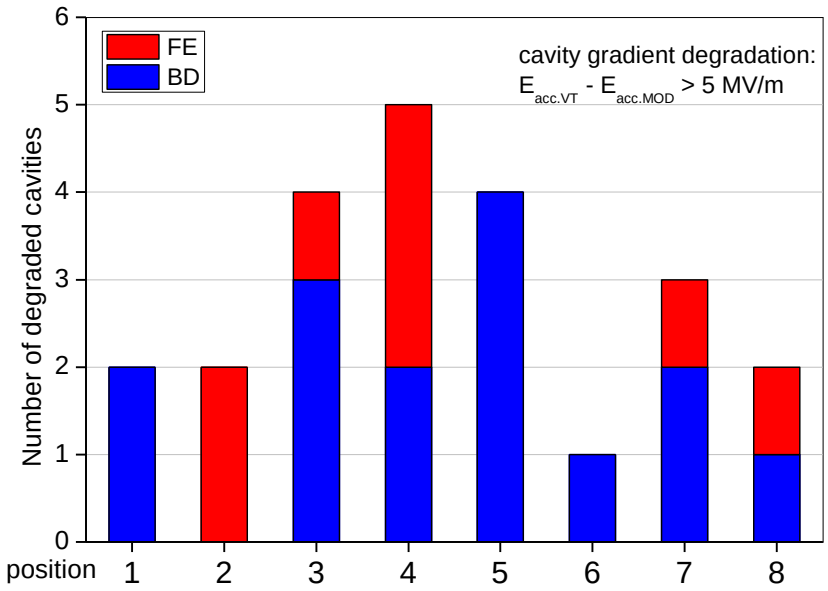



*Preliminary data; results are not published*

# Observations: Position in module



- Dependence on position in module + kind of limitation:




- **Operational gradient:**
**About 2/3** limited by quench!
- **Maximum gradient:**
**Nearly all** limited by quench!

Additional information:
No correlation between position and amount of degradation

- Comparison to **FLASH-modules** (with leak check after pos. 4):

| Position of Cavity in modules | P1 | P 2 | P 3 | P 4 | P 5 | P 6 | P 7 | P8 |
|---|---|---|---|---|---|---|---|---|
| No of cavities degraded @ position | 2 | 2 | **5** | 1 | 2 | **4** | 2 | 1 |

- **Middle positions affected stronger ???**



*Preliminary data; results are not published*

# Possible explanations: TTC 2011



- From **TTC 2011** for 3 analyzed cavities:
  - "**No differences to other cavities** in line found in assembly log book in respect of
    - particulates loading
    - assembly times
    - leakage found
    - RGA"
  - No hint for defect of any hardware for cleaning, pumping, etc.

  => **"NO provable explanation for degradation w/o FE"**

- After removal of He-tank: vertical test with SeSo + T-Map followed by Optical Inspection:
  - Z88 recovered w/o any treatment !!!???
  - AC127 with dark spot at equator 2
  - Z133 nothing special found at (unsafe?) quench location

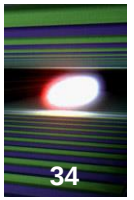
  **=> reinvestigation under discussion**

# Possible explanations



- TTF special topic meeting at Saclay (Nov 2014)
- **Transportation** (DESY => Saclay => DESY)
  - transportation tests with individual cavities => no indication
  - transportation of individual cavities from vendors to DESY in identical boxes => no degradation (?)
  - ongoing: Retest of 9 cavities after transport to Saclay and back to DESY
- **Critical cleanroom processes** from vertical test to module test:
  - cleanroom assembly of power coupler (procedure + "dirty" coupler)
  - cleanroom connection of string incl. "flushing" with ultrapure gas
  - several pumping and venting cycles
- **Other possible explanations**:
  - improper cooling of HOM's => unlikely (no "recovery effect" observed)
  - "hard" Multipacting => no indication (see above)
  - strong processing event in first run causing material displacement => no indication, but difficult to distinguish to "normal" processing

# Verifying / excluding explanations




- Transportation: Retest of 9 cavities after transport to Saclay and back to DESY
  => Result??
- Reproduce cleanroom procedures several times with individual cavities (w/o tank) and check performance in vertical test (incl. diagnostics)
  => for XFEL difficult due to man power + infrastructure limitation
- Restart individual horizontal tests
  => for XFEL NOT possible due to man power (+ infrastructure) limitation
- Disassembly of modules and analysis of individual cavities
  => done for TTC 2011 => some reinvestigation necessary?
  => for XFEL **NOT** possible due to schedule
- More ideas???

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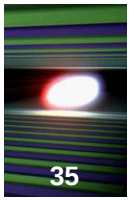
# Summary




- Vertical cavity testing, module testing and all work flows at AMTF are well established + in full operation

- Vertical acceptance test performance is well above specification
- Re-treatment gives significant improvement => worthwhile effort!

- String and module assembly procedures successfully transferred to CEA Saclay + Alsyom resulting in good module results above specification with room for improvement

- No explanation for cavities with decreased performance

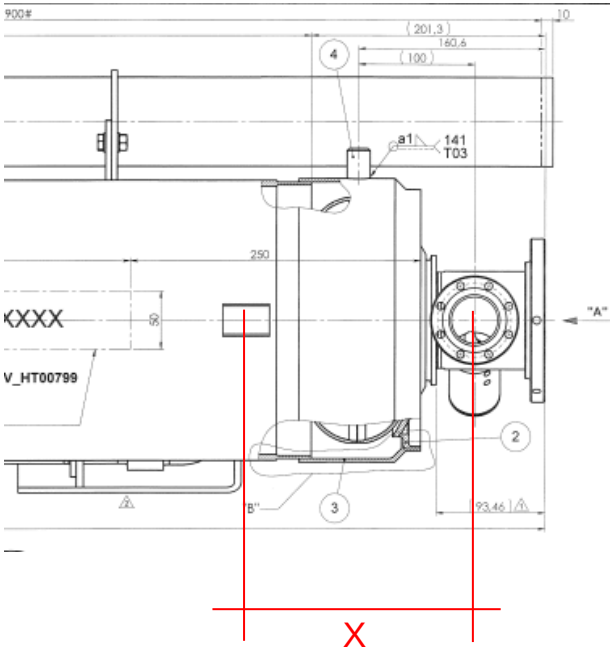
Thanks to all colleagues of
- E. Zanon
- Research Instruments
- CEA Saclay /Alsyom
- INFN Milano
- IFJ-PAN
- DESY
for their material, information and support

# Additional slides

# Vertical test => string assembly II



- **Mechanical constraints:**
- He-Tanks
  One critical dimension NOT well-defined in DESY drawings
  => assembly not possible at all positions in module
  Solution:
  - cavities shortened by 1mm
  - “sorting” wrt. position in module




- Q-values of critical HOM out of expected range (few cavities):
  - reason with RI under investigation
  - sorting in dedicated module

# 2-Phase Line (Service Pipe) Welding done in Routine Operation