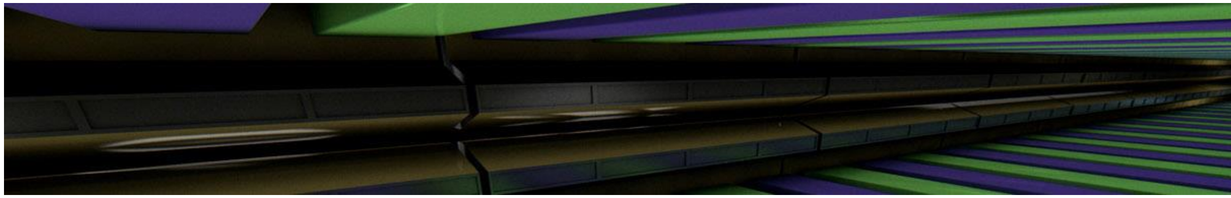
European XFEL



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Performance of Superconducting Cavities for the European XFEL

Detlef Reschke – DESY
for the EU-XFEL Accelerator Consortium

INFN Istituto Nazionale di Fisica Nucleare

DESY

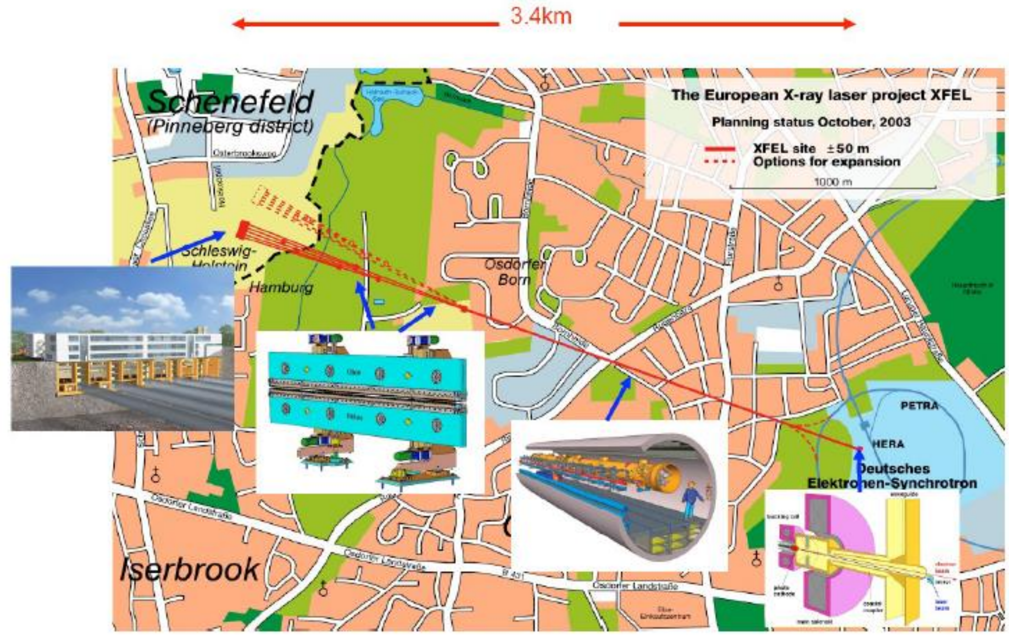
HELMHOLTZ | ASSOCIATION

European XFEL

Outline

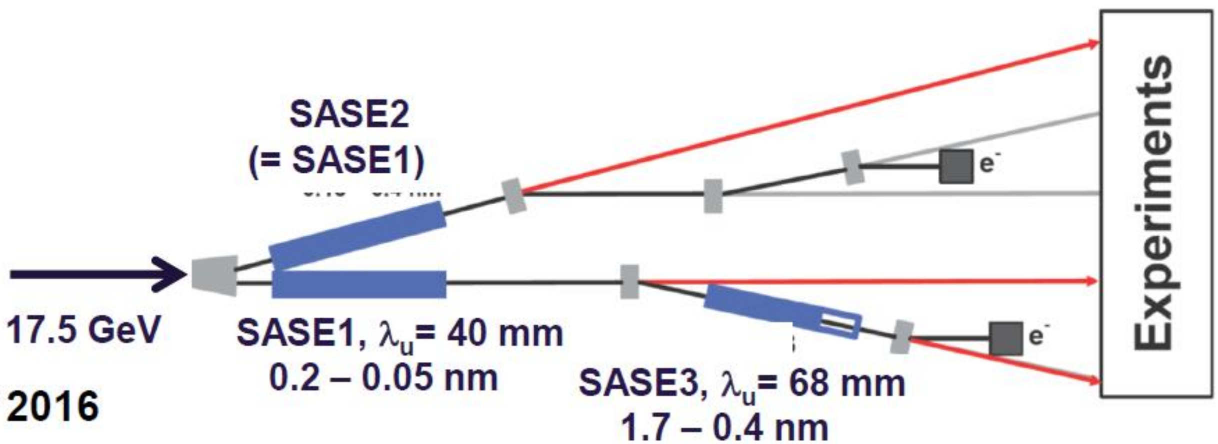
- European XFEL Linear Accelerator
- Cavity Production
- Vertical Acceptance Test
- Cryomodule Test
- Injector commissioning: - 1.3 GHz Injector Module
  - 3.9 GHz Third Harmonic System
- cw R&D on XFEL Cryomodules

The European XFEL
Built by Research Institutes from 12 European Nations



Some specifications
- Photon energy 0.3 - 24 keV
- Pulse duration ~ 10 - 100 fs
- Pulse energy few mJ
- Superconducting linac. 17.5 GeV
- 10 Hz (27 000 b/s)
- 5 beam lines / 10 instruments
  - Start version with 3 beamlines and 6 instruments
- Several extensions possible:
  - More undulators
  - More instruments
  - …….
  - Variable polarization
  - Self-Seeding
  - CW operation

First electron beam 2nd half of 2016



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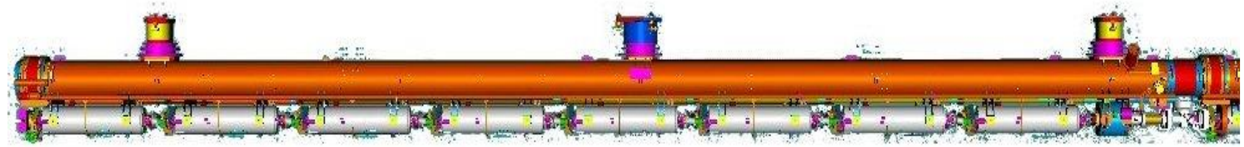
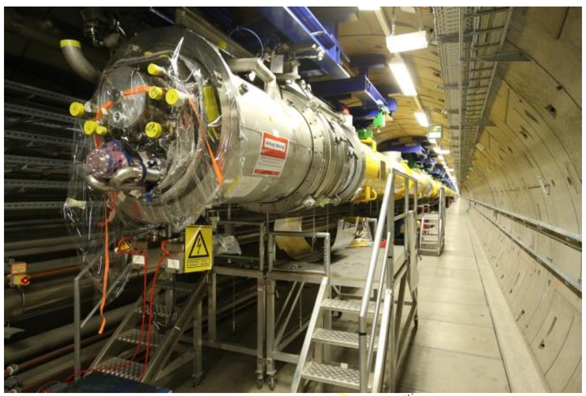
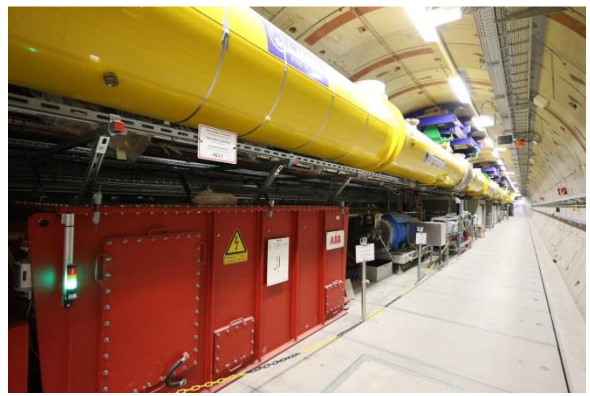
Accelerator Complex for 17.5 GeV

100 + 1 accelerator modules

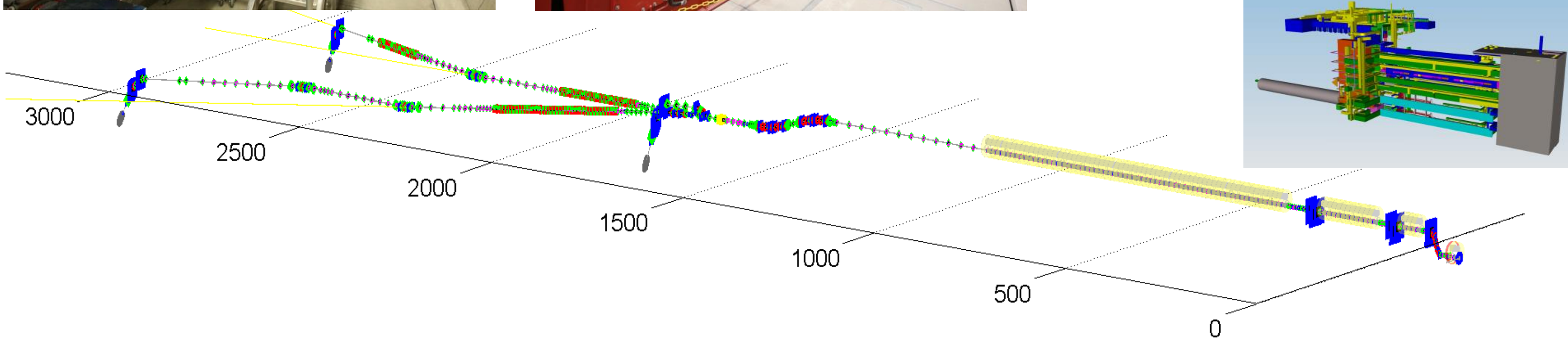


808 accelerating cavities
1.3 GHz / 23.6 MV/m





25 + 1 RF stations
5.2 MW each



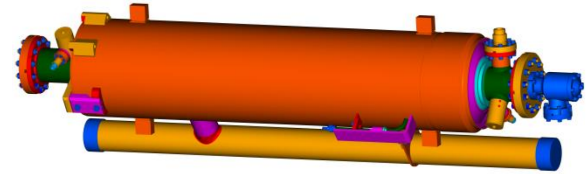
Cavity production: Preparation Phase

- Define final **cavity design**
  => TESLA design with minor design changes
- Establishing **surface treatment recipes**
  => based on app. 50 prototype cavities
- **Industrialization of main Electropolishing surface treatment**
  => set up of EP facilities at 2 companies
- Single-cell cavity R&D program (several aims)
- Preparation of **detailed specifications**
  => mechanical fabrication, surface treatment, HT integration, transport concept
- Finalize a concept for **documentation and data transfer**
- Qualification + selection of **Nb / NbTi material vendors**
  => 2 new companies
- Concept for fulfilling **PED requirements**
- Establishing **"Long pulse" vertical acceptance test**
  => protect HOM feedthroughs
- R&D on Large Grain Nb material

Courtesy W. Singer

Cavity production

- Contract allocated to Research Instruments (RI, Germany) and E.Zanon (EZ, Italy) in **equal shares end 2010**:
  - 560 series cavities
  - 24 cavities w/o He-tank for QC and further R&D (EU funded: "ILC-HiGrade")
  - Option: 240 series cavity
    => Order allocated end 2012/beginning 2013 in **equal shares**

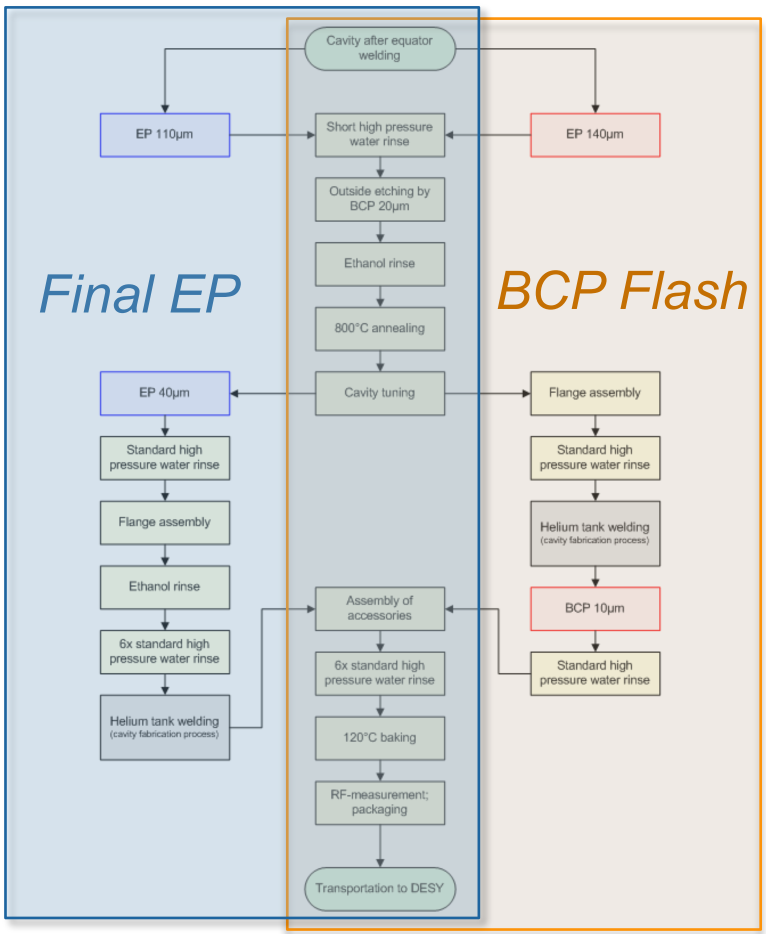


- **All Nb / NbTi material provided** by DESY (~ 24420 pieces)
  => includes ordering, PED-applicable QC + parts tracking, shipment

- Order placed following **"Build-to-Print" strategy**:
  - Production has to follow specifications precisely
    => close supervision by expert team + frequent visits + regular reporting (no resident expert at vendor)
  - **No performance guarantee** by vendors

Cavity Surface Preparation

- **Two schemes** for the final surface treatment:
  - **- E. Zanon: Final 10µm BCP** (“BCP Flash”)
  - **- Research Instr.: Final 40µm EP**



Successful mechanical production and surface preparation at both vendors!

No performance guarantee resulted in DESY taking responsibility for:

- the risk of unexpected low gradient or field emission
- **retreatment** (good cooperation/agreements with both vendors)

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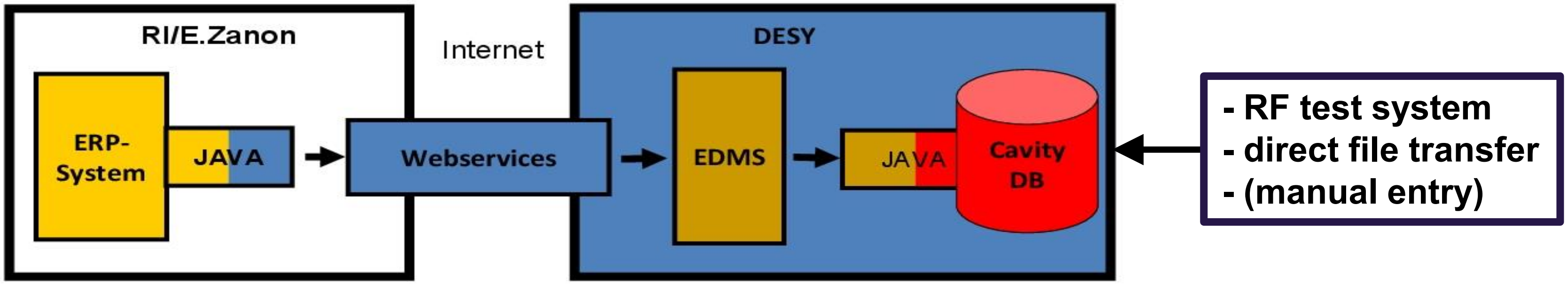
Quality Management + Documentation

- Key technical documents: **Technical Specifications + Change Reports**
- Quality Process based on **Quality Control Plan** (also for PED) including:
  - Vendor internal QA, QM system
  - Microsoft Project Plan for tracking of progress + schedule
  - **Non Conformity Reports NCR**:
    Documentation of all NC's including a proposal for correction procedure
  - Stepwise release of production (**Acceptance Levels** 1, 2, 3)
- All production documents (specifications, protocols, PED data, etc.) recorded electronically in **data management system (EDMS)**
- Data analysis in **cavity data base**

TUPOW001



- **Request Tracked e-mail** communication ("tickets")

Courtesy W. Singer

Transportation + Incoming Inspection

Transportation:

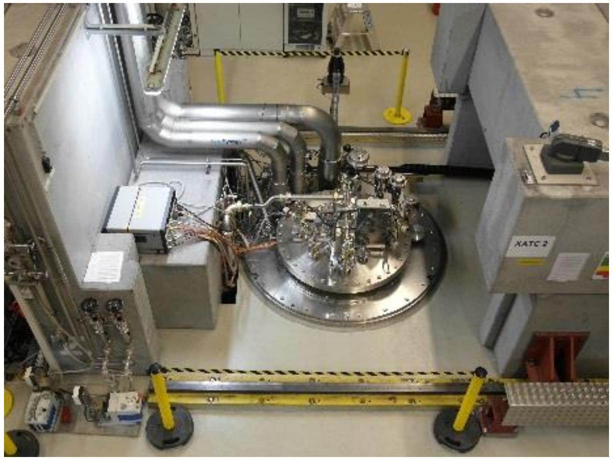
- "Cavity ready for test" requires well-defined transport concept
- Transport under vacuum
  => avoid particle transport
- Dedicated boxes for horizontal transport by truck (Vendor => DESY => Saclay)
- **No performance degradation observed**

Incoming inspection at DESY

- Basic mechanical, electrical, RF checks + final vacuum leak check before test
- Idea: Check for damages during transport
- Found: - Assembly errors + contaminations
  - Mechanical + electrical damages
  - Few leaks

  => 54 Cv's back to vendor
- **Incoming Inspection is mandatory**

Vertical tests at AMTF



Statistics of Cavities + Vertical Acceptance Tests

- Cavity production finished with last delivery in Mar 2016:
  - (800 + extra 4) Series Cavities
  - 24 ILC "HiGrade"-Cavities (w/o He-tank; QC)
    - 8 since equipped with He-tank and used for XFEL
  - 16 Cavities for infrastructure commissioning
    - 4 since used for XFEL

=> 816 cavities available and vertically tested for XFEL

- Analysis of vertical acceptance tests includes
  - Series Cavities
  - ILC "HiGrade"-Cavities (w/o He-tank)
  - NO infrastructure commissioning tests

- Stable average **vertical test rate ~40 tests/month** achieved
- 1225 vertical tests (few additional tests due to returns from string assembly possible)

VT-CM comparison: USABLE GRADIENT

Vertical Test – min of

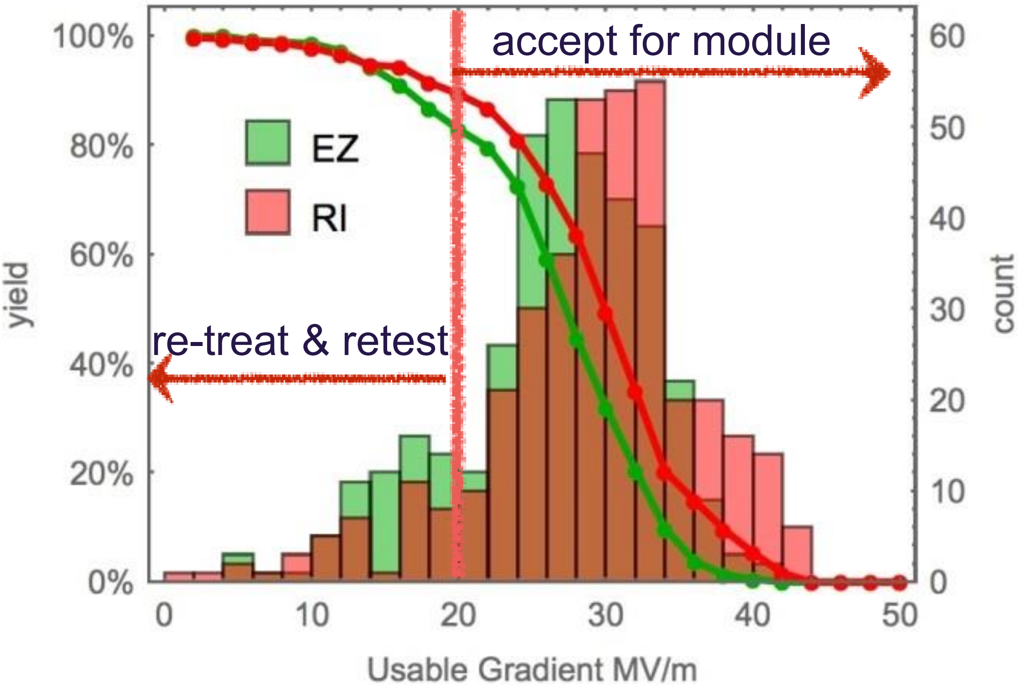
- Maximum gradient (quench, RF power)
- FE limit (top/bottom X-ray)
- Q_0 limit (= 10^{10})

Cryomodule – min of

- Maximum gradient (quench)
- FE limit (front/back X-ray)
- RF power limit at 31 MV/m

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

Results: Usable Gradient "As received"



	RI	EZ	Total
Tests	375	367	742
G_{AVG} (MV/m)	29.1	26.4	27.8
G_{RMS} (MV/m)	7.4	6.6	7.1
yield @ 20MV/m	89%	83%	86%
yield @ 26MV/m	73%	59%	66%
yield @ 28MV/m	63%	45%	54%

- Both vendors well above Spec
- RI shows ~ 3MV/m in average more than EZ:
  a) final EP
  b) low gradient quenches at EZ
- Several cavities with < 20 MV/m accepted "as received", especially if
  a) limitation = "bd" +
  b) no FE
- Average Q-values for both vendors:
  $Q_0(4\ MV/m) = 2.1 \cdot 10^{10}$
  $Q_0(23.6\ MV/m) = 1.3 \cdot 10^{10}$
- Missing ~90 cavities "as received"?

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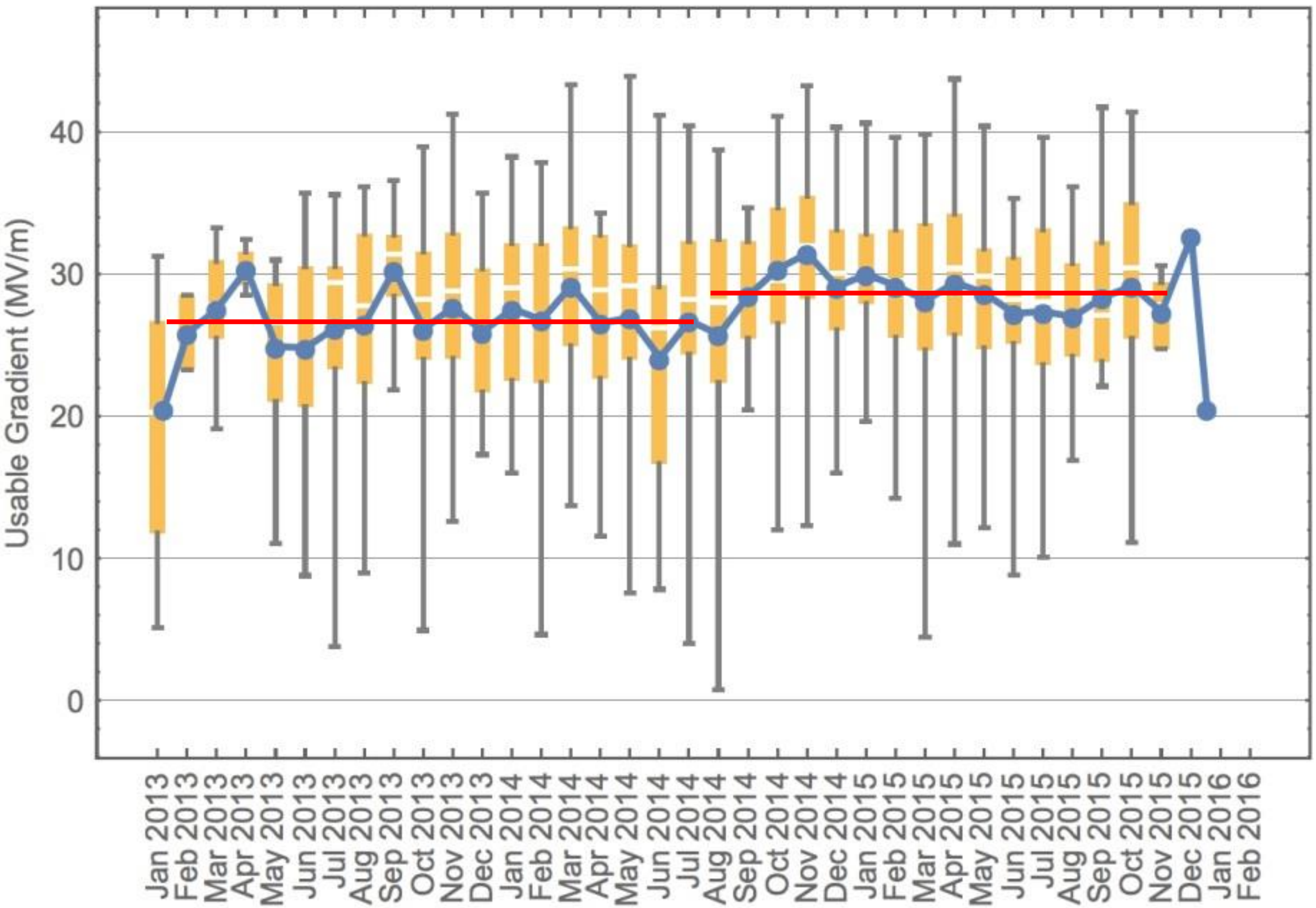
Trend of Usable Gradient "As received"



Good stability of average usable gradient over full production period

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Retreatments

- Why cavities w/o "as received" test?
  ("as received": first test after delivery to DESY + cavity conform to Spec)

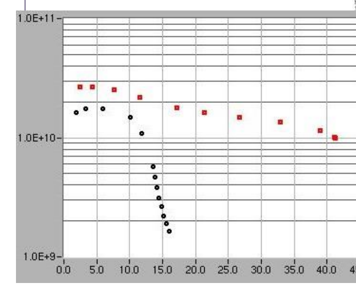
- Three main categories for retreatment (rework):
  - **Non-Conformities after delivery from vendor** (~ 90 Tests)
    (mechanical, vacuum, defects, …)
    => retreatment/rework at DESY or vendor depending on NC-type
  - **Performance** (~160 Tests)
    (acceptance criteria for gradient or Q-value not met)
    - mainly by field emission (+ "Quench", "low Q")
    => first + successful retreatment **H**igh **P**ressure Ultrapure Water **R**inse
    $<E_{acc, usable}>$: 19 MV/m => 26 MV/m
    $<Q_0(4\ MV/m)>$: $2.1 \cdot 10^{10}$ => $2.4 \cdot 10^{10}$
  - Non-Conformity during string assembly (21 Cv)

NON - CONFORMANCE REPORT

NON – CONFORMANCE NAME:	CAV_FE00186_NCR_for_Retreatment_01
CAVITY NR:	CAV_FE00186
RETREATMENT COUNTER:	01
DESCRIPTION:	Defect of feedthrough: NCR for Retreatment of Cavity
REASON OF NCR:	Defect of feedthrough
DESCRIPTION OF DEFECT	Pick-up feedthrough broken => to be exchanged
Short Description of Repair:	exchange of flange/antenna and HPR and after exchange of Pick up
Recommended Action:	exchange of flange/antenna
Recommended Action:	HPR
Recommended Action:	
Comments:	after exchange of Pick up feedthrough: retest at AMTF

DETECTION

Authors:	D. Reschke	
Date:	16.08.2014	
Location		
Place:	AMTF	
	Vertical Cryostat	--
	Preparation Platform	--
	Insert Number	--
Other:	during incoming inspection	



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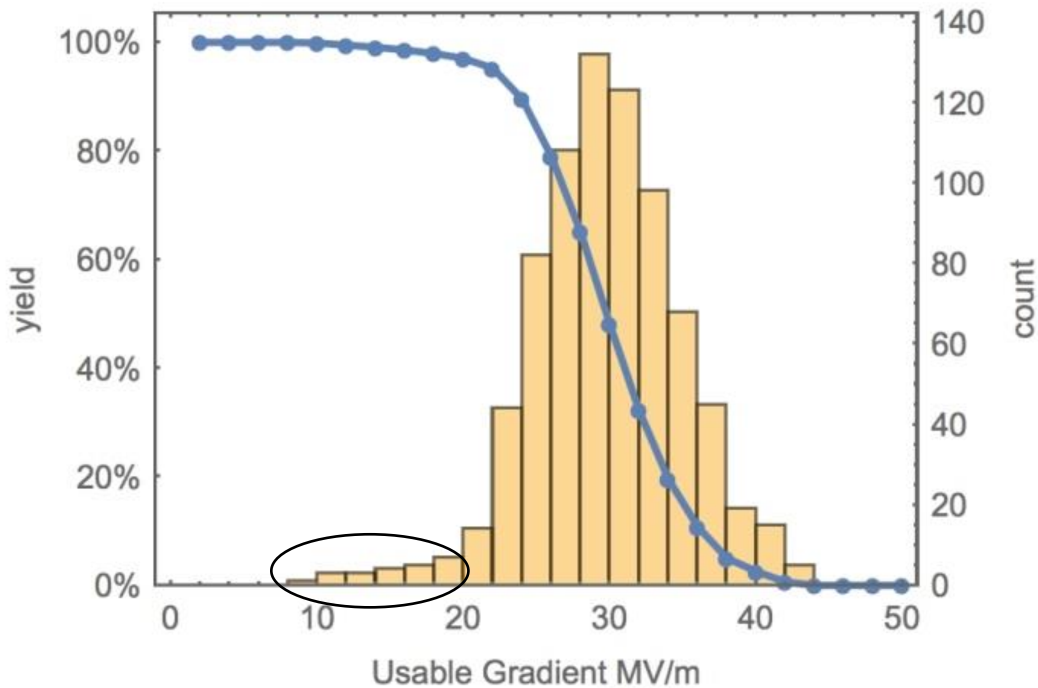
Analysis of Cavity Results

- Fully statistical approach; (nearly) no individual cavity analysis
  => simplified vertical test procedure at 2K:
  - $Q_0(E_{acc})$, - fundamental mode spectra, - HOM-check (partially)

- *Work in progress*:
  Analysis and possible correlations for $E_{acc,max}$, Q-value + x-rays
  - Nb-material: Vendor dependency
  - Cavity with vs. without He-tank
  - Surface treatment (not vendor)
  - Dependence on test infrastructure (RF test stand, cryostat, test inserts, …)
  - Cool down procedure
    => no special procedure applied, bad instrumentation, …
  - "Processing" vs. degradation in case of field emission; degradation after quench
  - Optical inspection, local repair
  - …
  - Error analysis

WEPMB007

Finally: “Send to Saclay“



Tests	**> 810**
G_{AVG} (MV/m)	29.8
G_{RMS} (MV/m)	5.1
yield @ 20MV/m	97%
yield @ 26MV/m	79%
yield @ 28MV/m	65%

- (nearly) all cavities shipped to CEA Saclay for string assembly
- average usable gradient: **~ 30 MV/m**
- includes cavities for three modules below 20 MV/m
  - Mainly low gradient quenches => retreatment not successful => retreatment would run out of schedule
  - Consequence of missing performance guarantee

Cryomodule Test at AMTF

- April, 20: **90 modules** arrived with ~87 modules rf tested (XM-3 excluded)

Statistics of Cryomodules + Cryomodule Tests

- Cryomodule assembly at CEA Saclay (=> see SRF2015, O. Napoly)

- Analysis of cryomodule tests: **April 20, 2016** (~87 cryomodules)

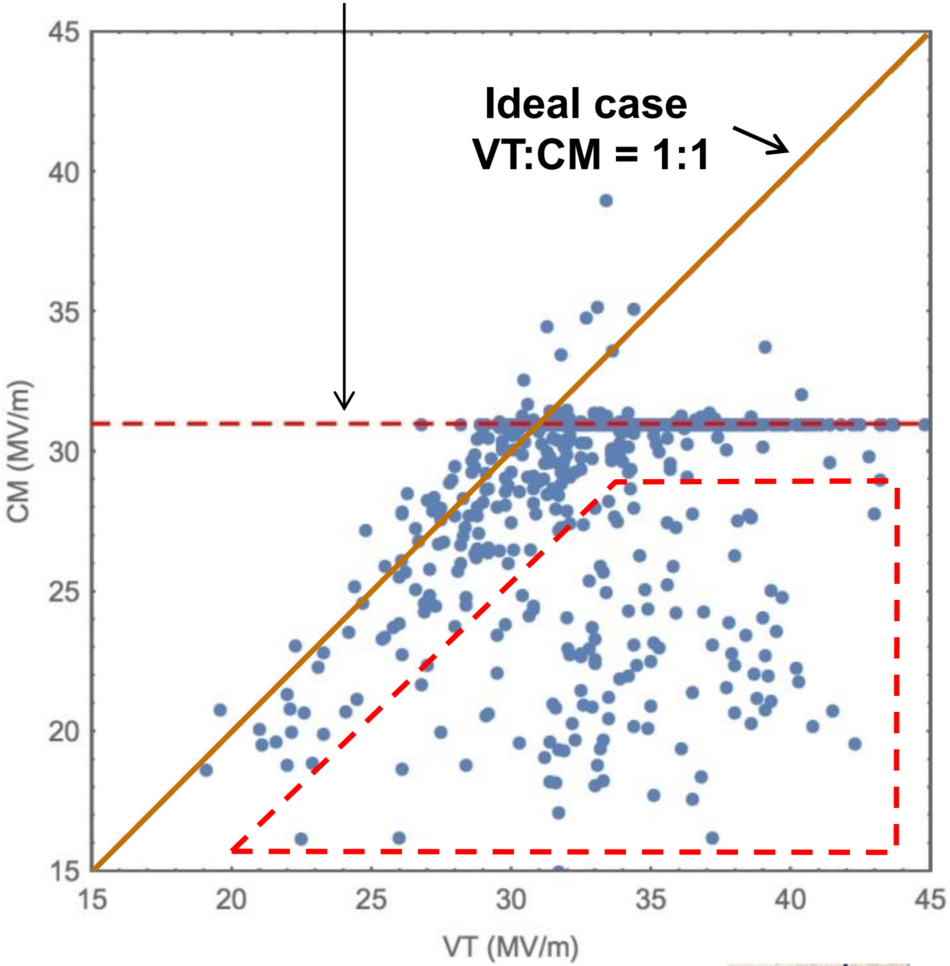
- Improved and optimized test procedure since June 2015
  => typical test duration reduced to < 15 days
  (assuming no non-conformities!!!)

- Non-conformities (causing significant delay):
  - cryogenic + vacuum leaks (mainly at temporary connections to test stand)
  - warm coupler part ("push rod" bellow leaks, assembly NC's, …)

Cryomodule – Vertical Test Comparison: MAX GRADIENT

- individual cavity comparison of max gradient

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



- **we lose between vertical and cryomodule test**

- average VT: **30.3 MV/m**
(clipped at 31 MV/m)
average CT: **28.7 MV/m**
(includes limit at 31MV/m)

Vertical Test - Cryomodule Comparison: USABLE / OPERATIONAL GRADIENT

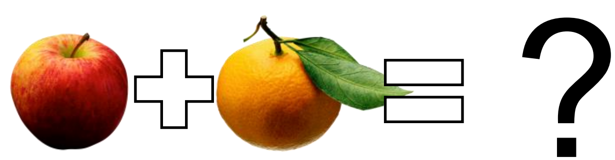
Vertical Test – min of

- Maximum gradient (**quench**)
- **FE limit** (top/bottom X-ray)
- **Q_0 limit** (= 10^{10})
- RF power limit at ~200 W

Cryomodule – min of

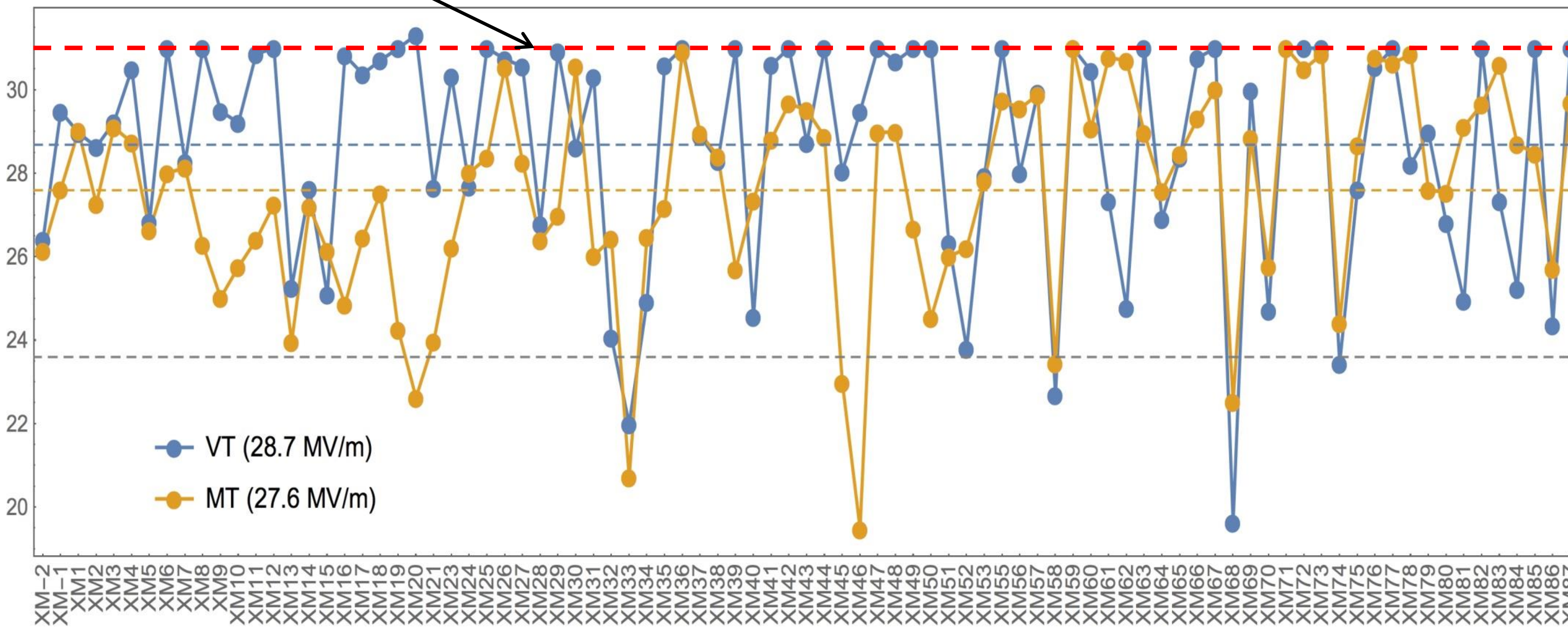
- Maximum gradient (**quench**)
- **FE limit** (front/back X-ray)
- not available
- **RF power limit** at 31 MV/m

when making comparisons,



Vertical Test - Cryomodule Comparison: Average cryomodule gradients

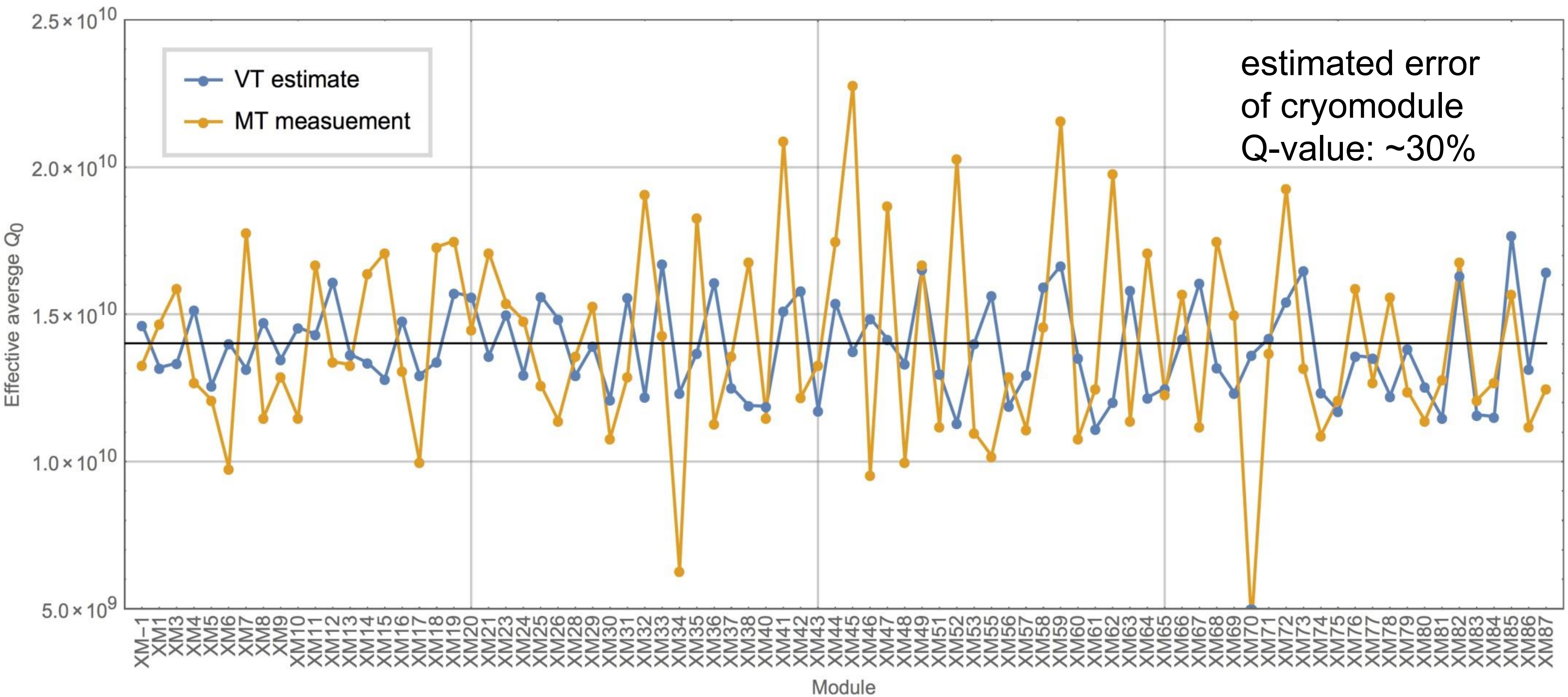
CM: upper limit due to 31 MV/m limit by RF power
VT: clipped at 31 MV/m



	N_{cavs}	Average	RMS	min	max
VT	695.	28.7	2.9	11.2	31.
CM	695.	27.6	4.5	10.5	31.

Average VT performance met within <4%

Vertical Test - Cryomodule Comparison: Q_0-values at ~20-23MV/m

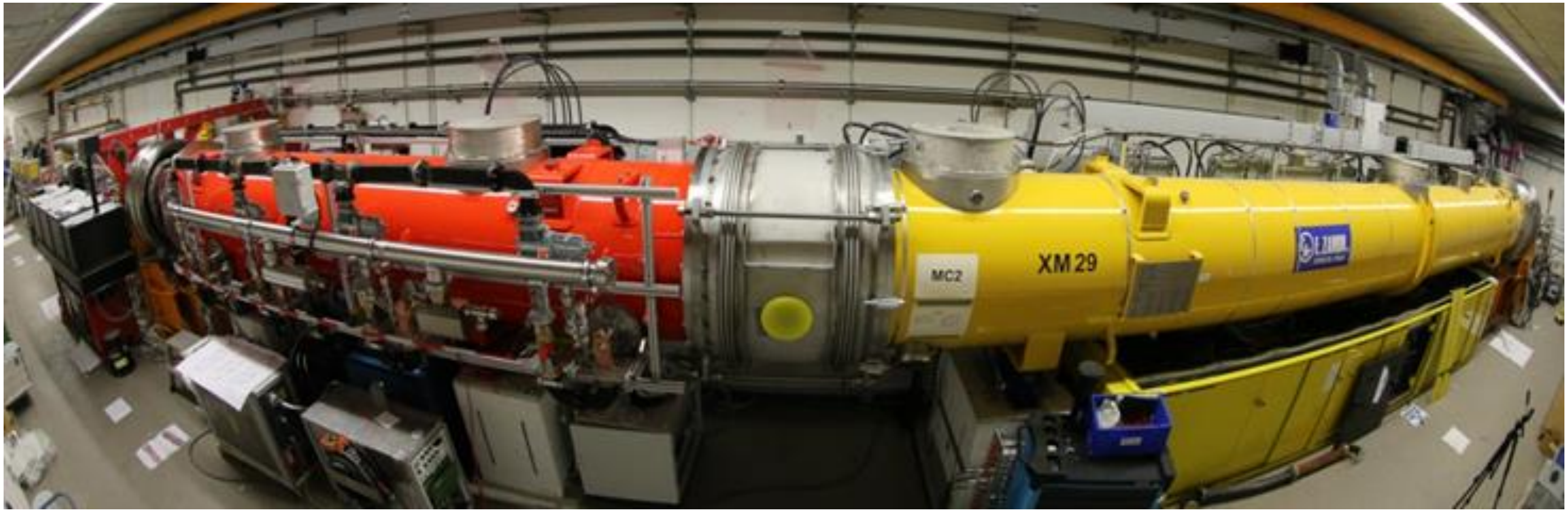


Average Q_0-value at ~20-23 MV/m: vertical ~1.4 x 10^{10}

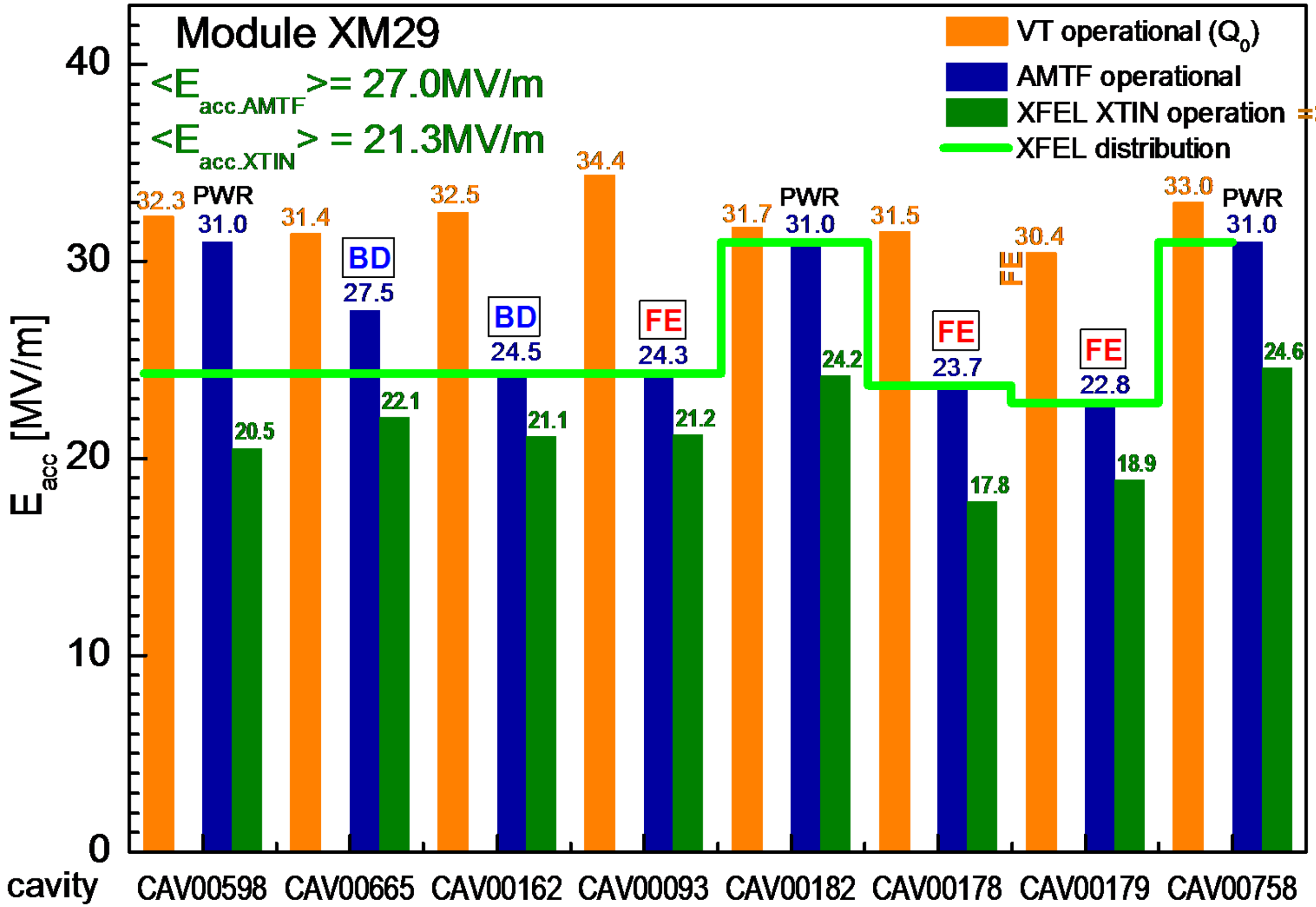
cryomodules ~1.4 x 10^{10}

Cryomodule Operation in the Injector

- Cold module operation started Dec 2015
- More about "Commissioning of the European XFEL Injector" see F. Brinker & W. Decking: TUOCA03



Injector Module Performance: First “cold” 1.3 GHz module A1 (XM29)



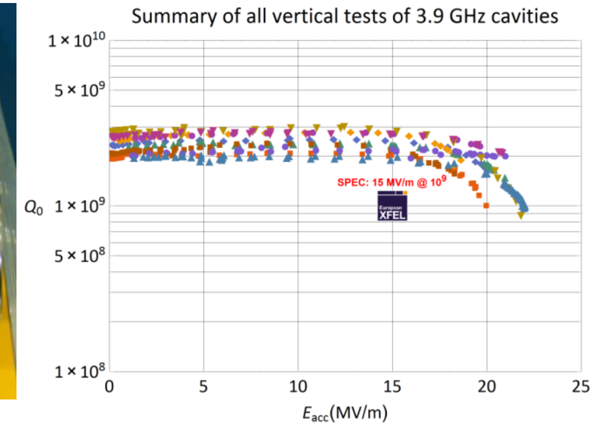
=> not cavity limited

Courtesy D. Kostin

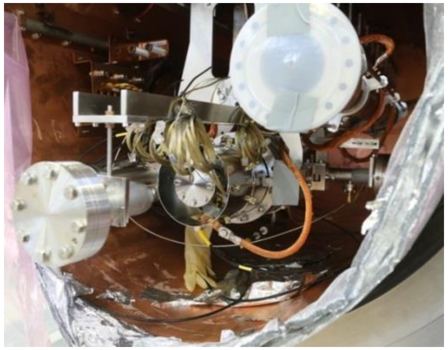
No cavity limitation during injector operation (up to **160 MeV** beam energy)

3.9 GHz Cavity Performances

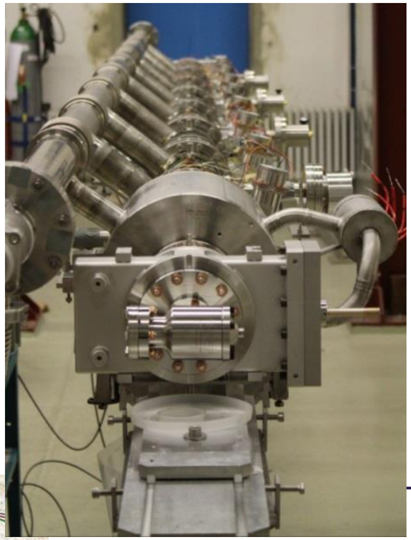
- VT of undressed cavities before integration and module assembly successful:
  Spec: 15 MV/m @ 10^9
  <VT>: 20.8 MV/m @ > 10^9



- Horizontal RF test of one fully equipped 3.9 GHz cavity up to 24 MV/m:
  => Cavity package validated (tuner, coupler, WG tuners)

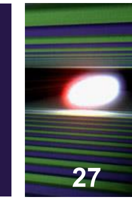


- String assembly:

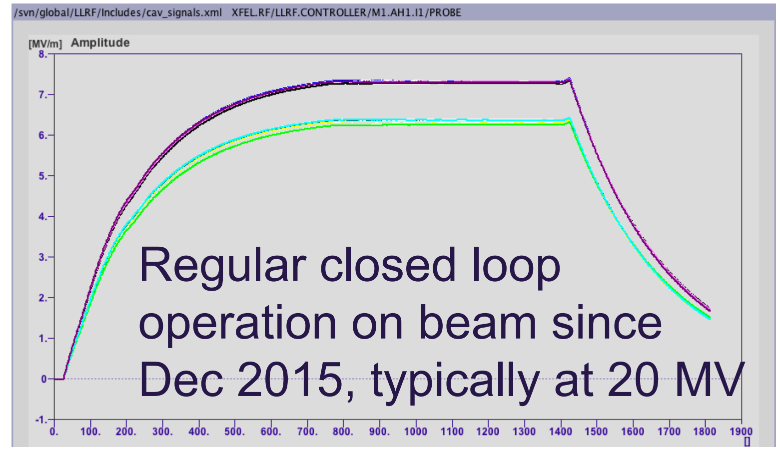


Courtesy
P. Pierini

Third Harmonic module in XFEL injector



- AH1 (3.9 GHz module) operating since the start of the Injector commissioning
  - Beam dynamics requirements: up to approx 30 MV
  - Successful tunnel operation: **tested >45 MV**

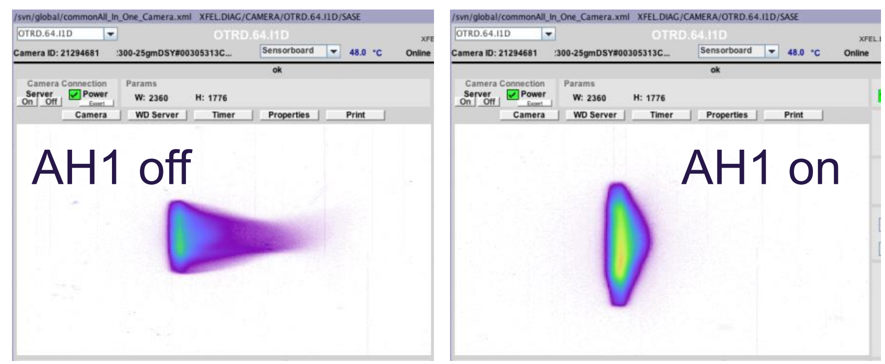


tunnel RF test environment much less accurate

(C7 is the first cavity to reach quench limit above VS setpoint of 45 MV)

Cav	Eacc (MV/m)	
	XTIN	VT
C1	18.1	21.0
C2	17.6	20.0
C3	18.7	20.8
C4	17.1	22.0
C5	18.2	21.0
C6	17.6	19.6
C7	17.7	20.0
C8	17.3	21.8

First evidence of linearization effect



Courtesy P. Pierini

- **Spare module in fabrication (with plans for CW tests)**

TUPOW005

European XFEL

cw R&D on EU-XFEL Cryomodules

EU-XFEL and FLASH originate from the TESLA collider and therefore they nominally operate (FLASH) and will operate (EU-XFEL) in so called short pulse (sp) mode

RF-pulses		Max RF DF [%]
Max RF pulse length incl. rise time [μs]	Rep. Rate [Hz]	
1400	10	1.40

Both accelerators are based on the SRF technology and thus have potential for much larger DF, up to 100% (cw).

Having **additional** cw and long pulse modes will allow for more flexibility in the time structure of the photon beams and will make both facilities even more attractive to the users.

Courtesy
J. Sekutowicz

European XFEL

cw R&D on EU-XFEL Cryomodules

Summary for series XFEL cryomodule in short pulse, long pulse (lp) and cw operation mode:

Courtesy J. Sekutowicz

Demonstrated Gradients

	Mode	sp	lp	cw
XM4 / FG	Max <Eacc> [MV/m]	31.8	19	15

Demonstrated Qo in lp/cw operation at **2K** and **1.8K**

Mode	lp (DF≈20%)	cw
XM4 / FG	2.0E10 @19MV/m	2.3E10 / **3.5E10** @15MV/m

- No quench was observed for cw/lp modes in all conducted tests.
- Maximum demonstrated DHL was 71 W in cw mode at ~15 MV/m. Operation was very stable. This proves that the E-XFEL cryomodule helium supply and return system can handle at least 77W dissipation.

Summary + Outlook

- Cavity production at both vendors successfully finished
- Vertical acceptance tests finished and well above Spec

- Accelerator cryomodule assembly and testing close to be finished
- Cryomodule tests well above Spec
  (some degraded cavities after string assembly)

- 1.3 GHz injector cryomodule and 3.9 GHz third harmonic system in successful beam operation

- Series 1.3 GHz cryomodule tested in cw / long pulse mode with excellent results

- Detailed analysis of VT and CM tests for correlations in progress
- EU-XFEL Linac commissioning in late 2016

Thanks to all colleagues of:

- IFJ-PAN Krakow (esp. J. Swierblewski, M. Wiencek)
- CEA Saclay
- INFN Milano (esp. L. Monaco)
- E. Zanon
- Research Instruments
- Daher Transkem
- Alsyom
- DESY

(esp. V. Gubarev, J. Schaffran, L. Steder, N. Walker, M. Wenskat, S. Yasar)