Performance Analysis of the European XFEL SRF Cavities, From Vertical Test to Operation in Modules

Nick Walker (DESY)

D. Reschke, J. Schaffran, L. Steder, M. Wenskat, DESY

L. Monaco, INFN Milano

- MO1A01 H. Weise “Status of the European XFEL”
- WE1A02 S. Berry “Assembly of XFEL cryomodules: Lessons and Results.
- This talk:
  - Vertical test (VT) results from 816 cavities
  - Cryomodule test results compared to VT
  - Predicted linac performance

} Statistical analysis

European XFEL

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 converted to series cavities
  - 16 Cavities for infrastructure commissioning (“RCV”, “DCV”)
    → 4 converted to series cavities

→ 816 XFEL series cavities available + vertically tested

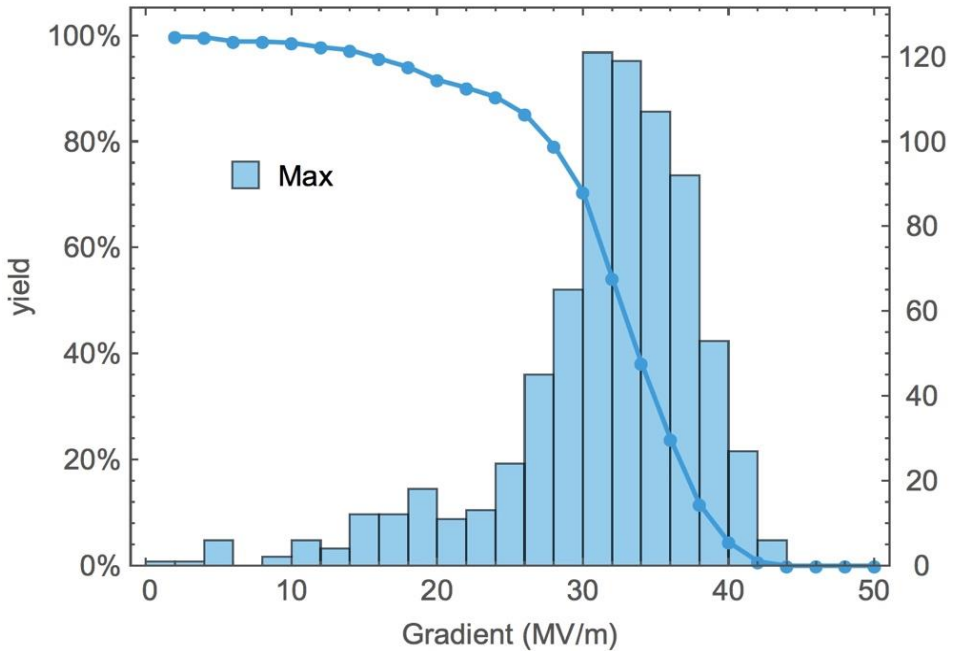
- Analysis of vertical acceptance tests includes
  - Series Cavities
  - ILC “HiGrade”-Cavities (w/o He-tank; QC)
  - NO infrastructure commissioning tests

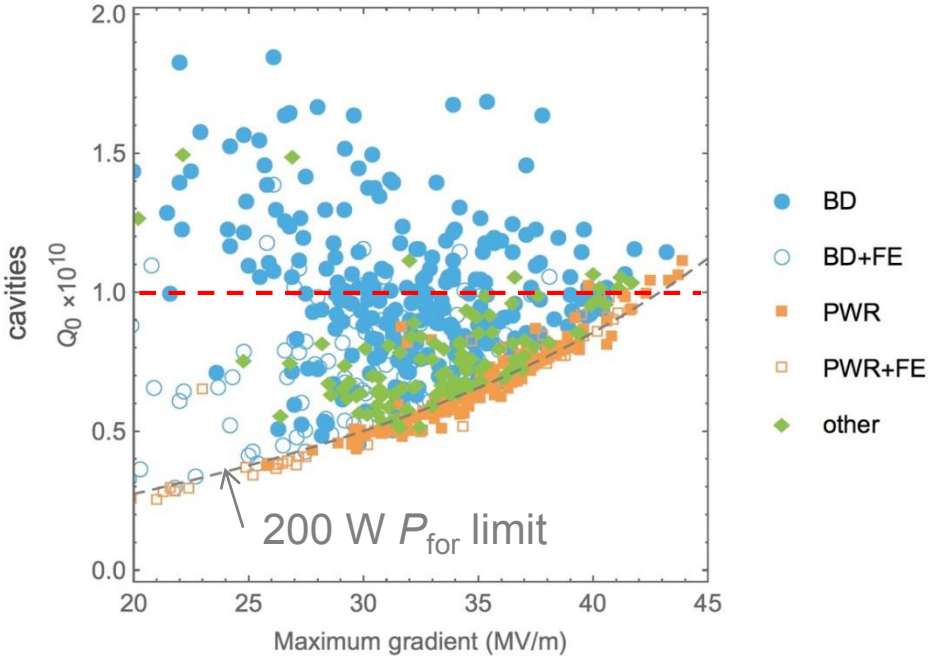
- Stable average **vertical test rate ~40 tests/month** achieved

European XFEL

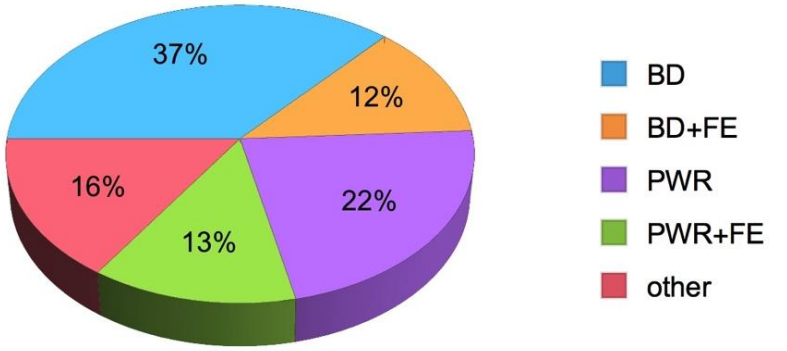
As Received Maximum Gradient in the VT

typical individual error: 10%



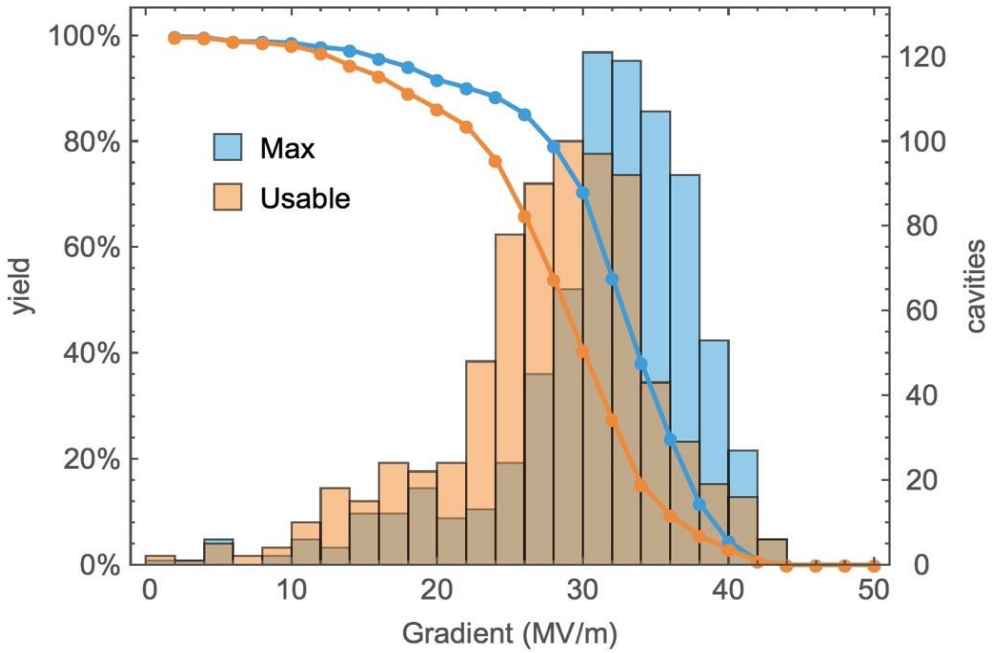


		Max
Average	MV/m	31.4
RMS	MV/m	6.8
Median (50%)	MV/m	32.5
Yield ≥20 MV/m		92%
Yield ≥26 MV/m		85%



As Received Usable Gradient in the VT

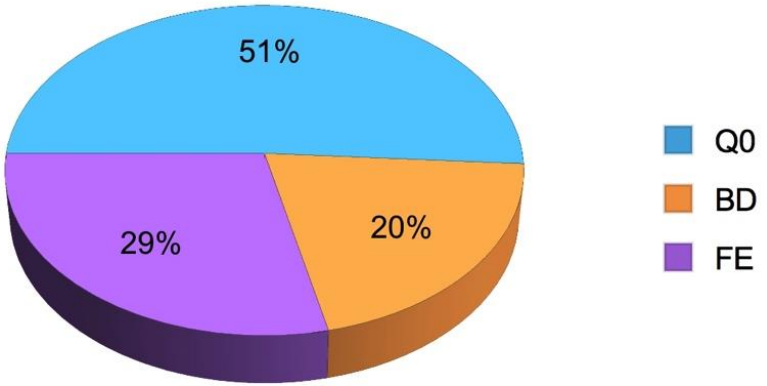
typical individual error: 10%



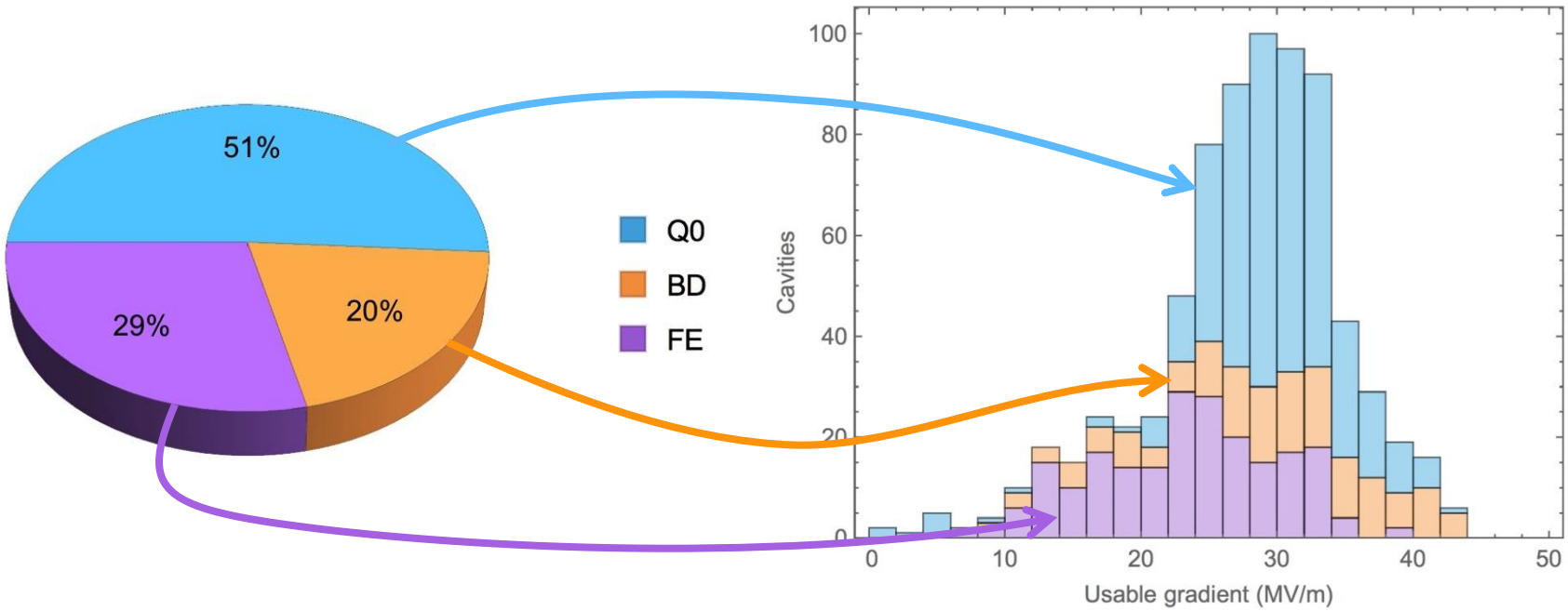
		Max
Average	MV/m	31.4
RMS	MV/m	6.8
Median (50%)	MV/m	32.5
Yield ≥20 MV/m		92%
Yield ≥26 MV/m		85%

- Include operations spec
  - $Q_0 \geq 1\times10^{10}$
  - FE threshold (X-ray)

→ Usable Gradient



Usable gradient: limiting effects

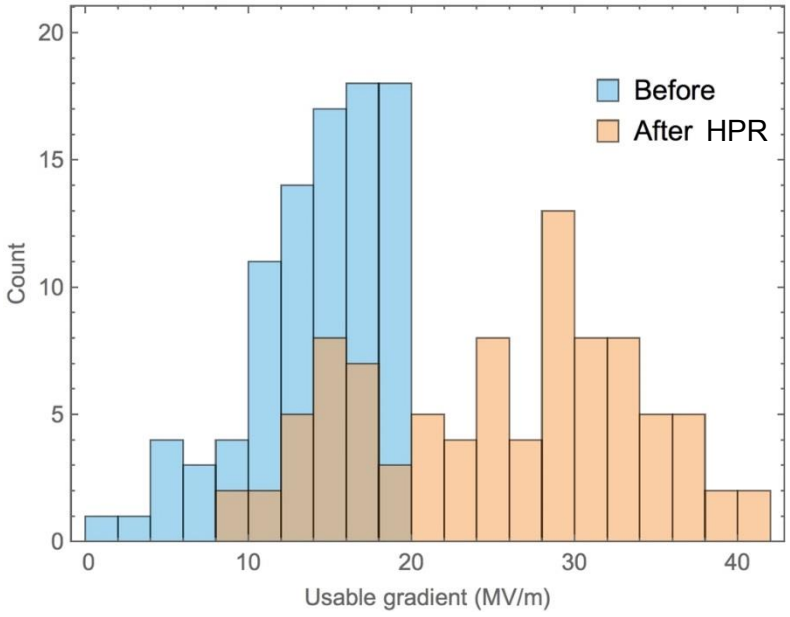


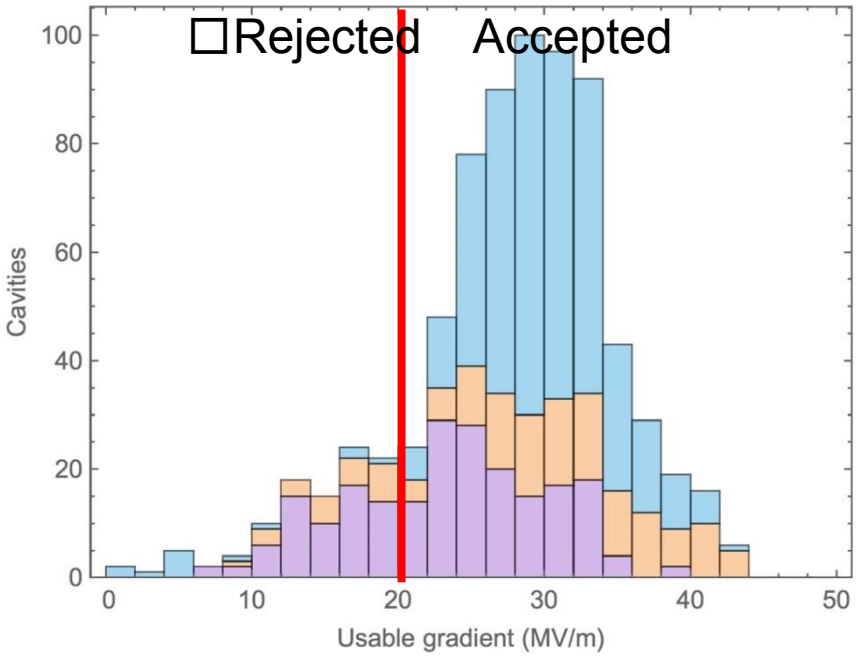
- Q_0 dominates at higher gradients (high-gradient Q-slope)
- Field Emission (FE) dominates <24 MV/m
- Quench (BD) not dominant –mostly higher gradients

European XFEL

Recovering low performance cavities

- E_{usable} <20 MV/m rejected
  - Approx. 15% cavities
- Sent for surface retreatment
  - Mostly High Pressure Rinse (HPR)
  - Small fraction Buffered Chemical Polishing (BCP) and/or “grinding”

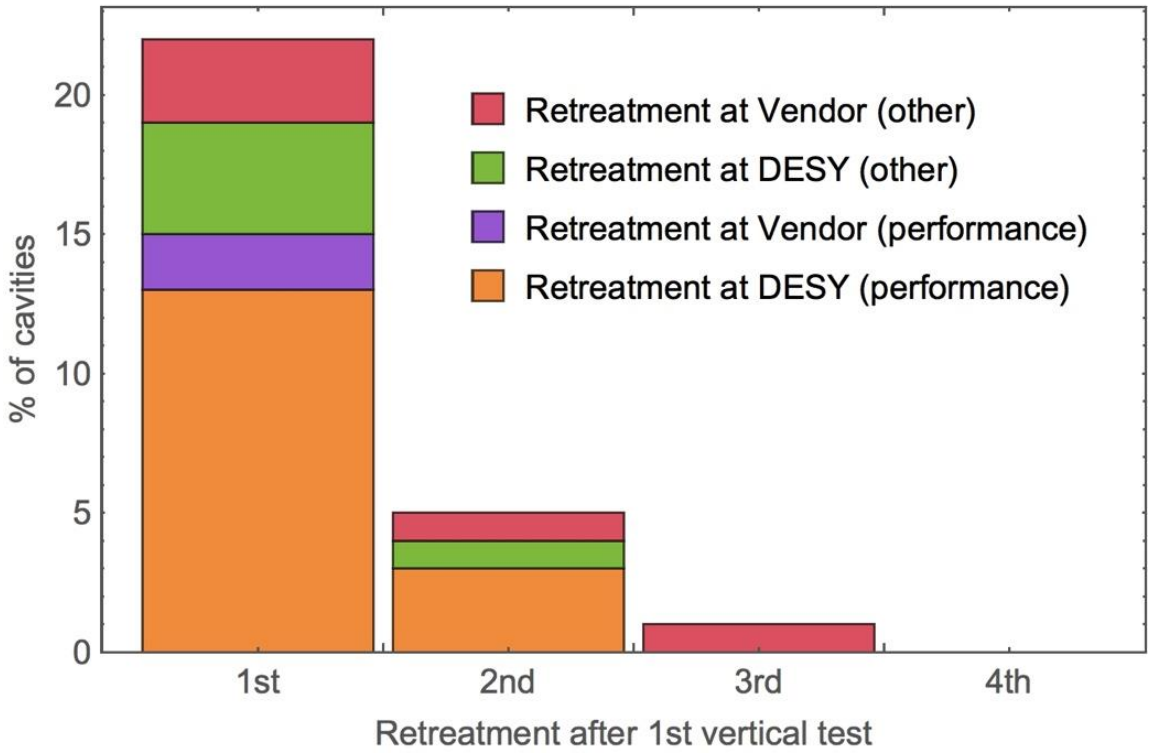




		Max	Usable
Average	MV/m	31.4	27.7
RMS	MV/m	6.8	7.2
Median (50%)	MV/m	32.5	28.7
Yield ≥20 MV/m		92%	86%
Yield ≥26 MV/m		85%	66%

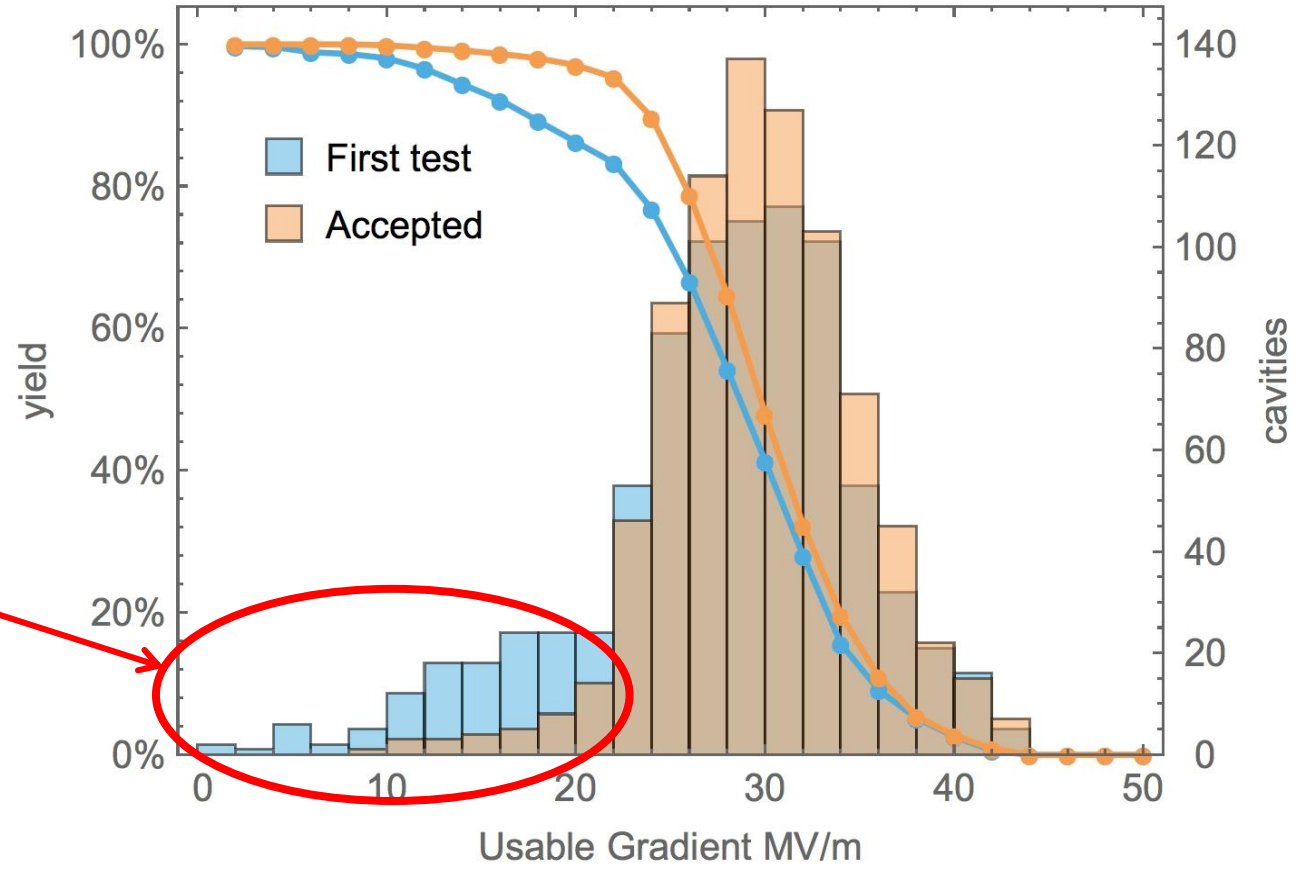
Number of retreatments after the 1st vertical test

- Approx. 22% of cavities had ≥1 retreatment
  - ~15% performance-driven
  - ~7% due to vacuum- and mechanical-related problems (mostly HPR)
- 5% had 2 or more retreatments.
  - including both chemical and mechanical (grinding)



Final performance (sent for module assembly)

- $\langle E_{\text{usable}} \rangle = 29.8 \pm 5.1$ MV/m



impact of retreatment

As received Q_0 performance

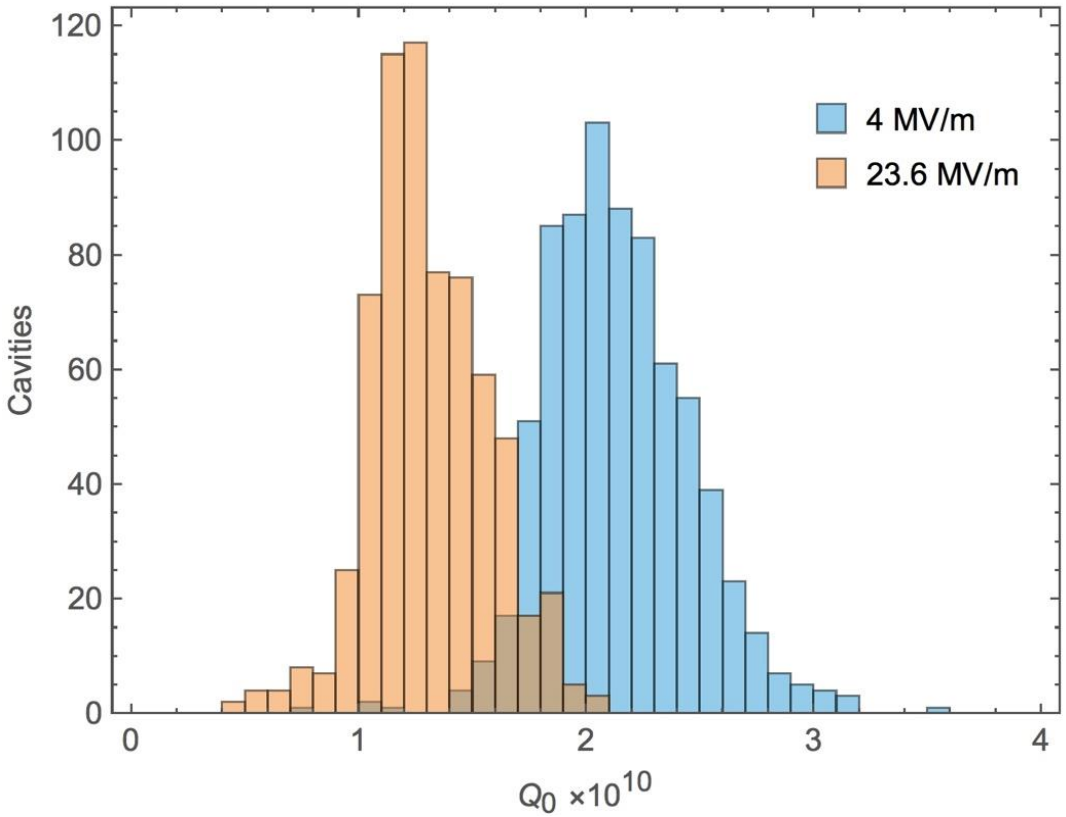
Average ±RMS:

4 MV/m: $2.1 \pm 0.3 \times 10^{10}$

23.6 MV/m: $1.3 \pm 0.3 \times 10^{10}$

Estimated measurement error 10-20%

XFEL spec: $\geq 10^{10}$



European XFEL

Cryomodule assembly at CEA Saclay

European XFEL

Cryomodule assembly at CEA Saclay

Cryomodule Assembly

Cryomodule assembly at CEA Saclay

the study shall cover clean room assembly and the assembly outside cleanroom

Startpoint: string assembly in cleanroom

(all parts are tested and ready for assembly)

Clean room assembly

Assembly outside cleanroom

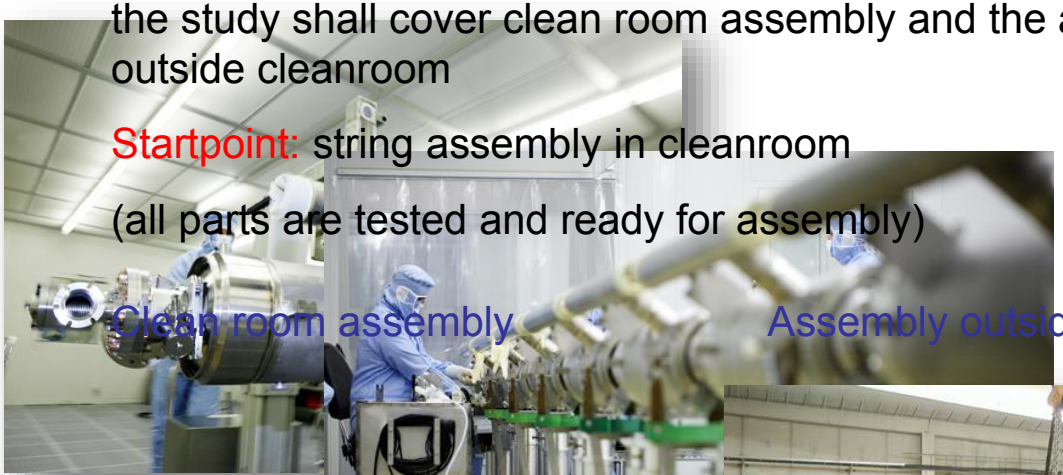
Cryomodule Assembly

Cryomodule assembly at CEA Saclay

the study shall cover clean room assembly and the assembly outside cleanroom

Startpoint: string assembly in cleanroom

(all parts are tested and ready for assembly)



Clean room assembly

Assembly outside cleanroom

LCFOA, FNAL, Sept 05; D. Proch, DESY

European XFEL

Cryomodule Test at AMTF

VT vs MT: Making Comparisons

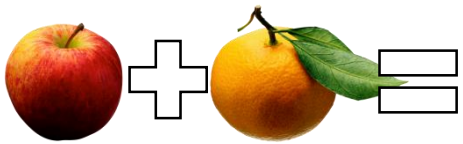
	VT	MT	
Maximum gradient	No administrative limit	limited to 31 MV/m	*True impact unknown (but can set an upper limit)*
Field Emission (X-Ray)	Two monitors above and below cryostat	Two monitors upstream and downstream of cryomodule axis	*Different geometry / calibration makes exact comparison difficult*
Q_0	RF measurement	~1 hour 2K cryoload measurement with all cavities on resonance	*No Q_0 limit taken in MT definition of usable gradient.*
General	CW measurement	Pulse RF measurement (10% duty cycle)	*Systematic errors and uncertainties*

European XFEL

VT vs MT: Making Comparisons

	VT	MT	
Maximum gradient	No administrative limit	limited to 31 MV/m	*True impact unknown (but can set an upper limit)*
Field Em (X-Ray)			*geometry / n makes mparison*
Q_0	RF measurement	4 hour 2K cryoload measurement with all cavities on resonance	*No Q_0 limit taken in MT definition of usable gradient.*
General	CW measurement	Pulse RF measurement (10% duty cycle)	*Systematic errors and uncertainties*

when making comparisons,

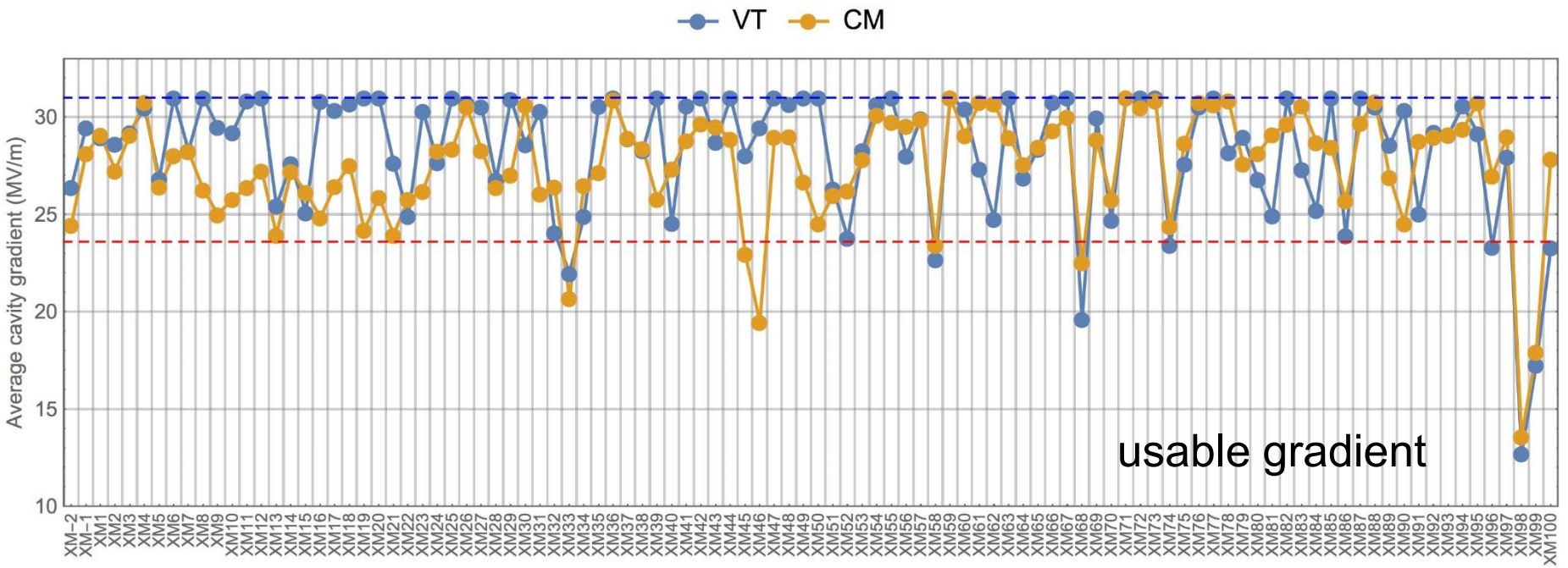


?

A quench (BD) below 31 MV/m can be compared

European XFEL

Cryomodule average gradient performance

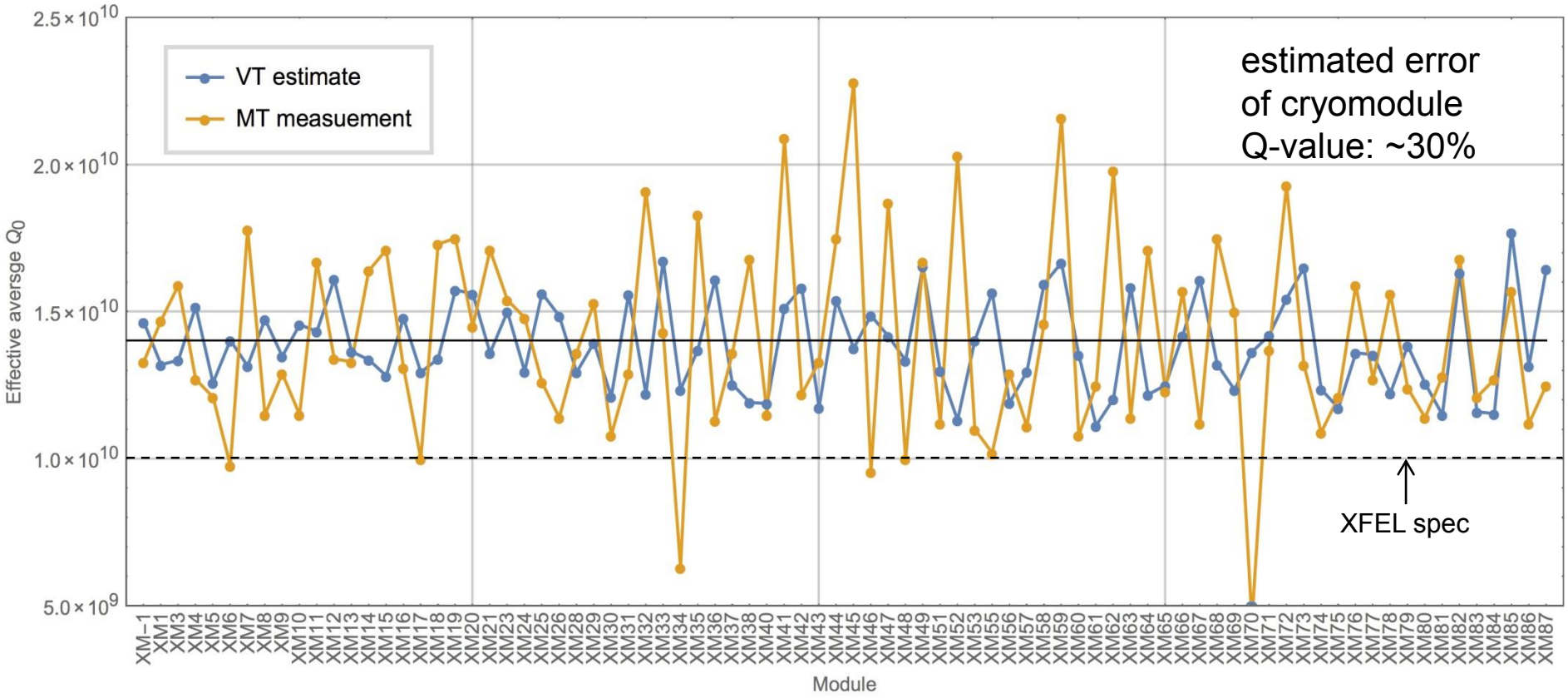


VT capped at 31 MV/m for fair comparison

	N_{cavs}	Average	RMS
VT	815	28.3 MV/m	3.5
CM	815	27.5 MV/m	4.8

~3% difference measured this way

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



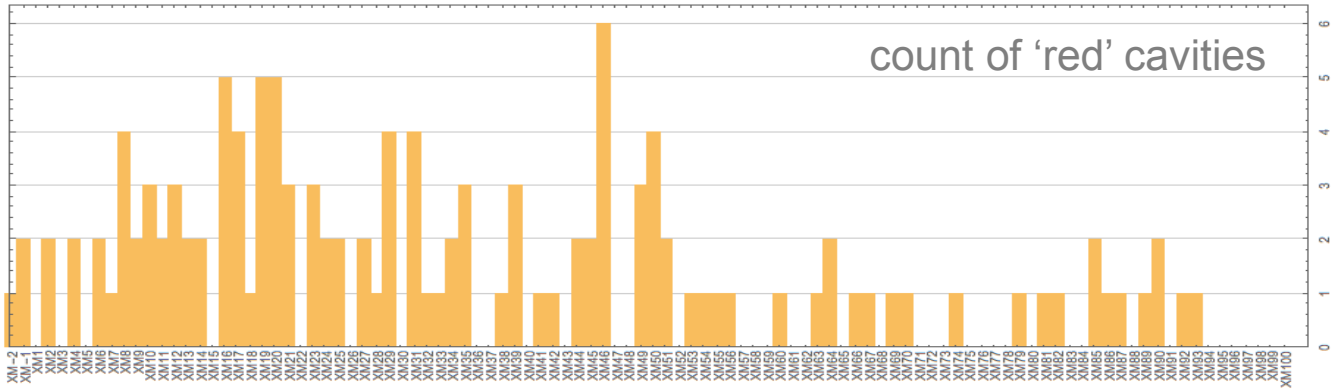
Average Q_0-value at ~ 23 MV/m: vertical 1.4×10^{10}

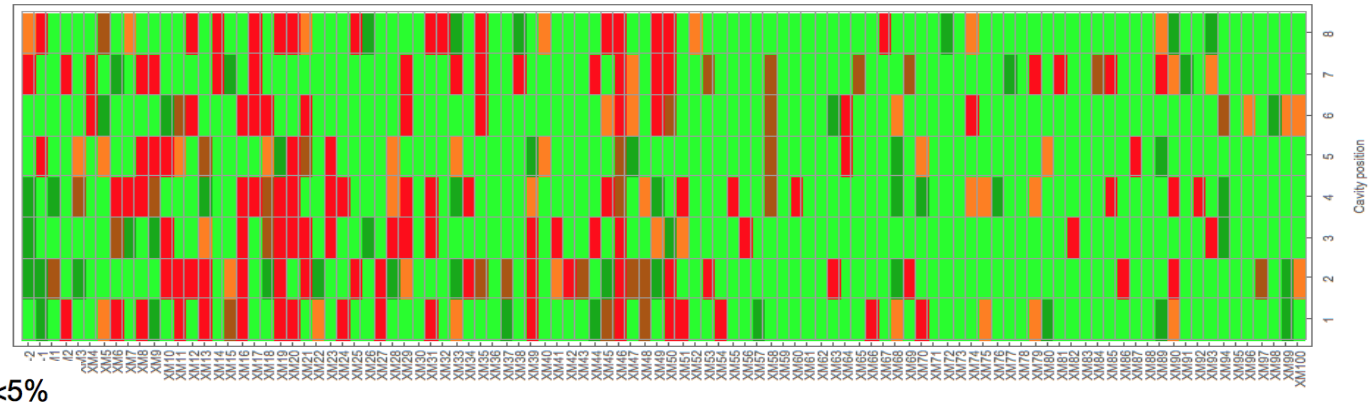
cryomodules **1.4×10^{10}**

European XFEL

Degradation matrix

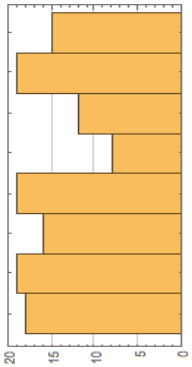
Degradation defined as ≥20% (red)





- <5%
- <10%
- <15%
- <20%
- ≥20%

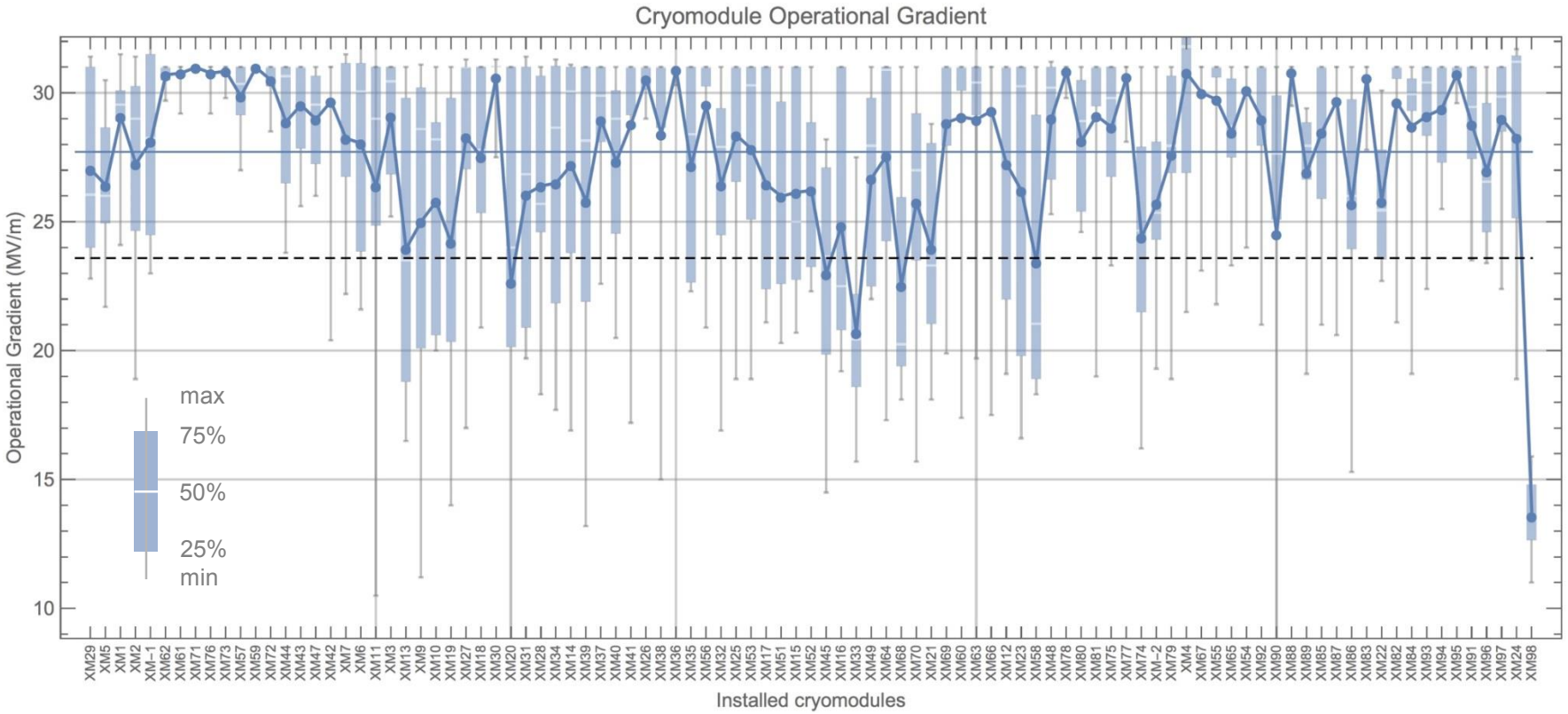
best place to be a happy cavity in a cryomodule



INFN DESY HELMHOLTZ ASSOCIATION

European XFEL

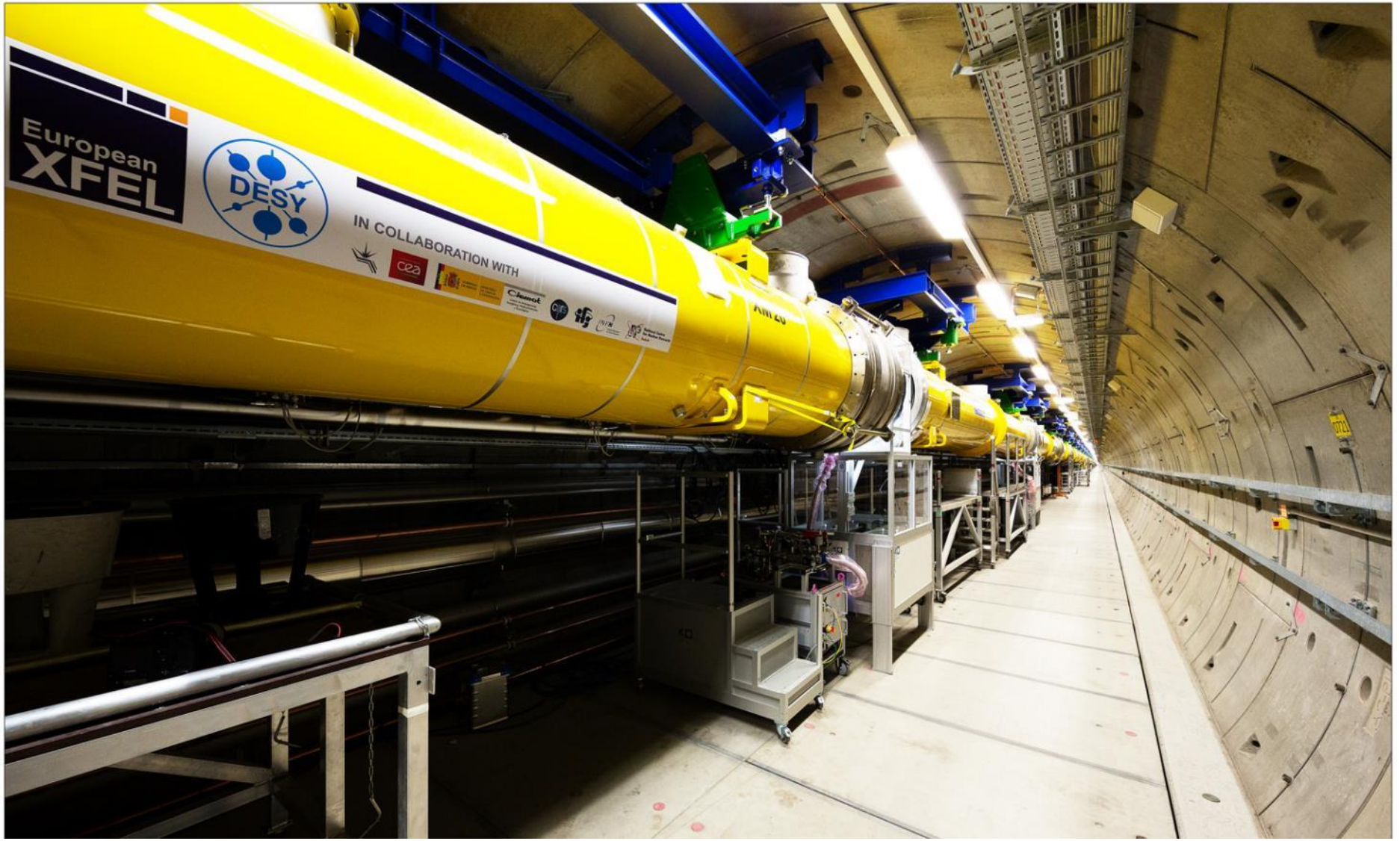
Cryomodule performance (AMTF module test)



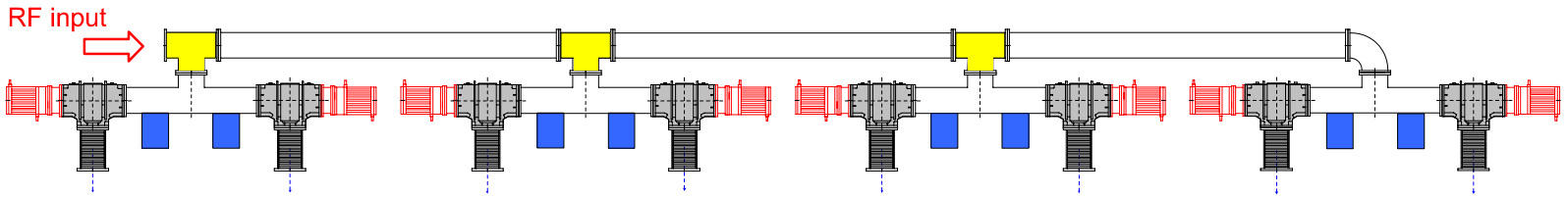
Average (blue line) is good but spread within modules is still quite large

→ “Fine tuning” of waveguide distribution to maximise energy gain.

Into the LINAC

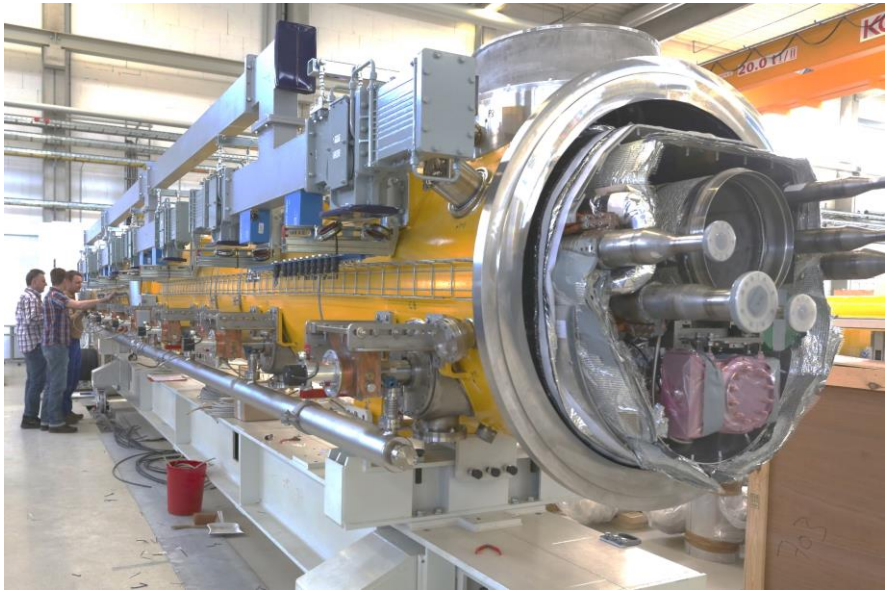


Impact of Waveguide Distribution (WD) system (Installed Gradient)



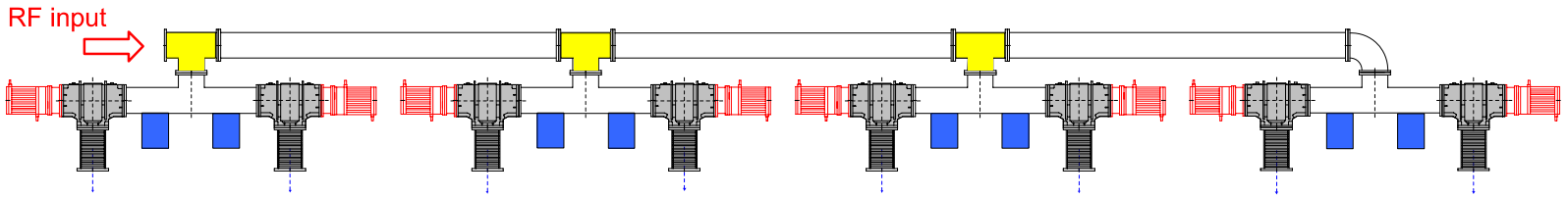
courtesy V. Katelev

- 1 10-MW klystron drives four modules (32 cavities)
- WD for cryomodules tailored for MT results
  - maximising voltage
  - up to 3dB difference between cavity pairs
- Allow up to 3dB split between adjacent cryomodule pairs
- Equal power output from two klystron arms



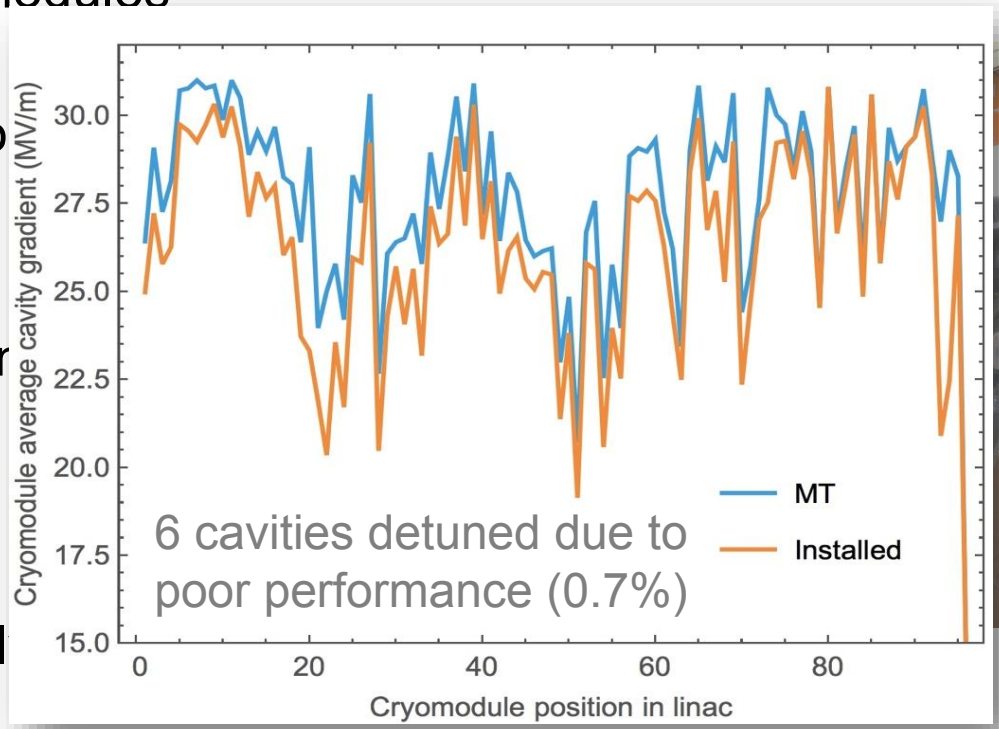
see THPLR067 Choroba, Katalev, Apostolov

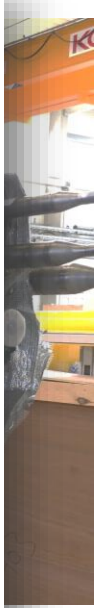
Impact of Waveguide Distribution (WD) system (Installed Gradient)



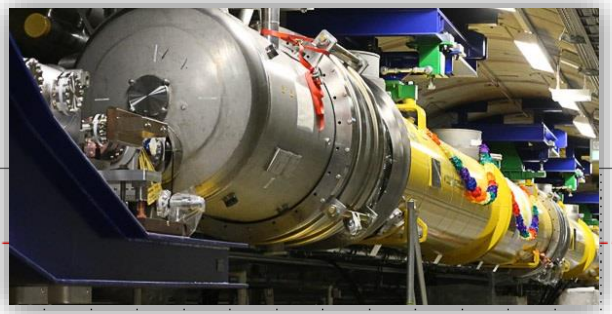
courtesy V. Katelev

- 1 10-MW klystron drives four modules (32 cavities)
- WD for cryomodules tailored fo results
  - maximising voltage
  - up to 3dB difference betweer cavity pairs
- Allow up to 3dB split between adjacent cryomodule pairs
- Equal power output from two kl arms

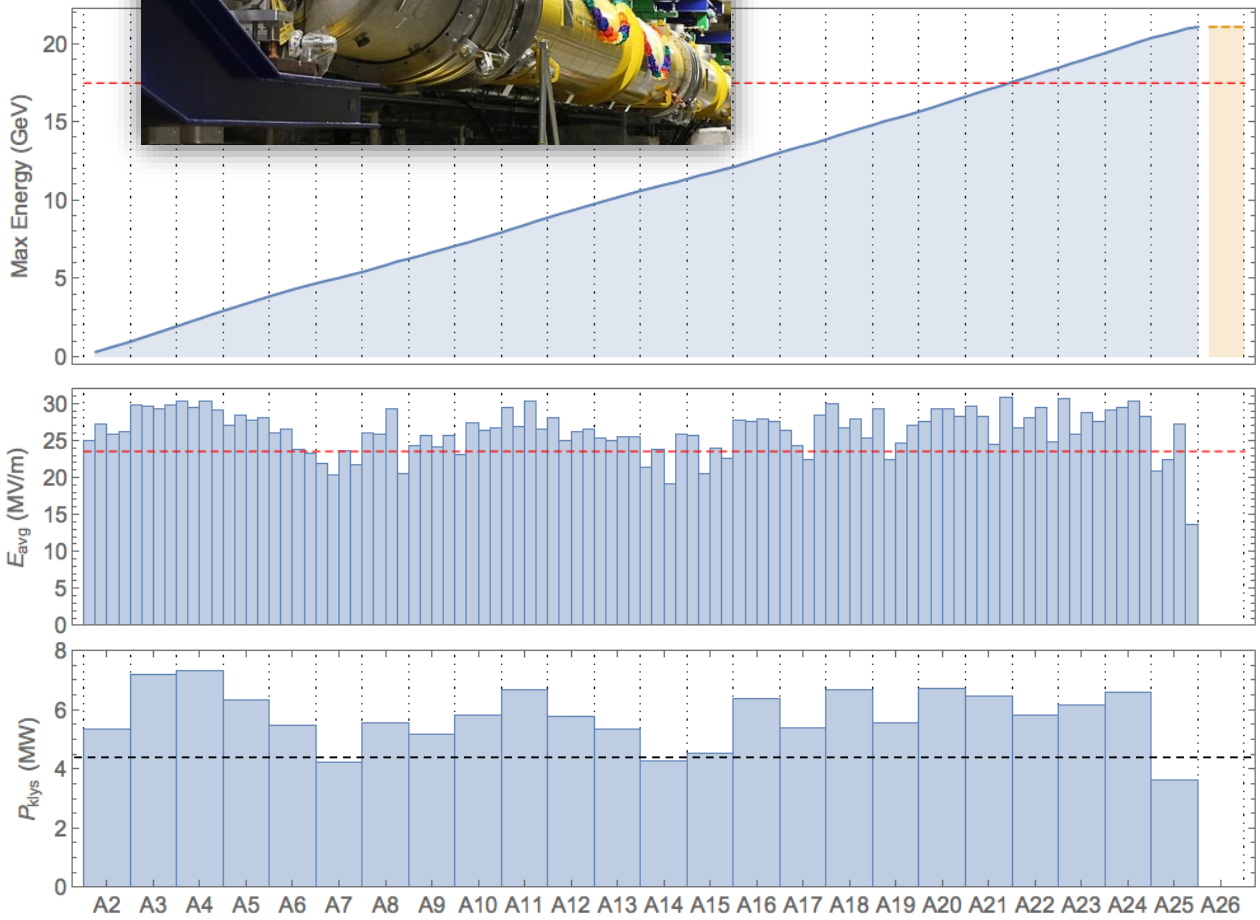




Projected installed energy profile



E_{max} ~ 20 GeV

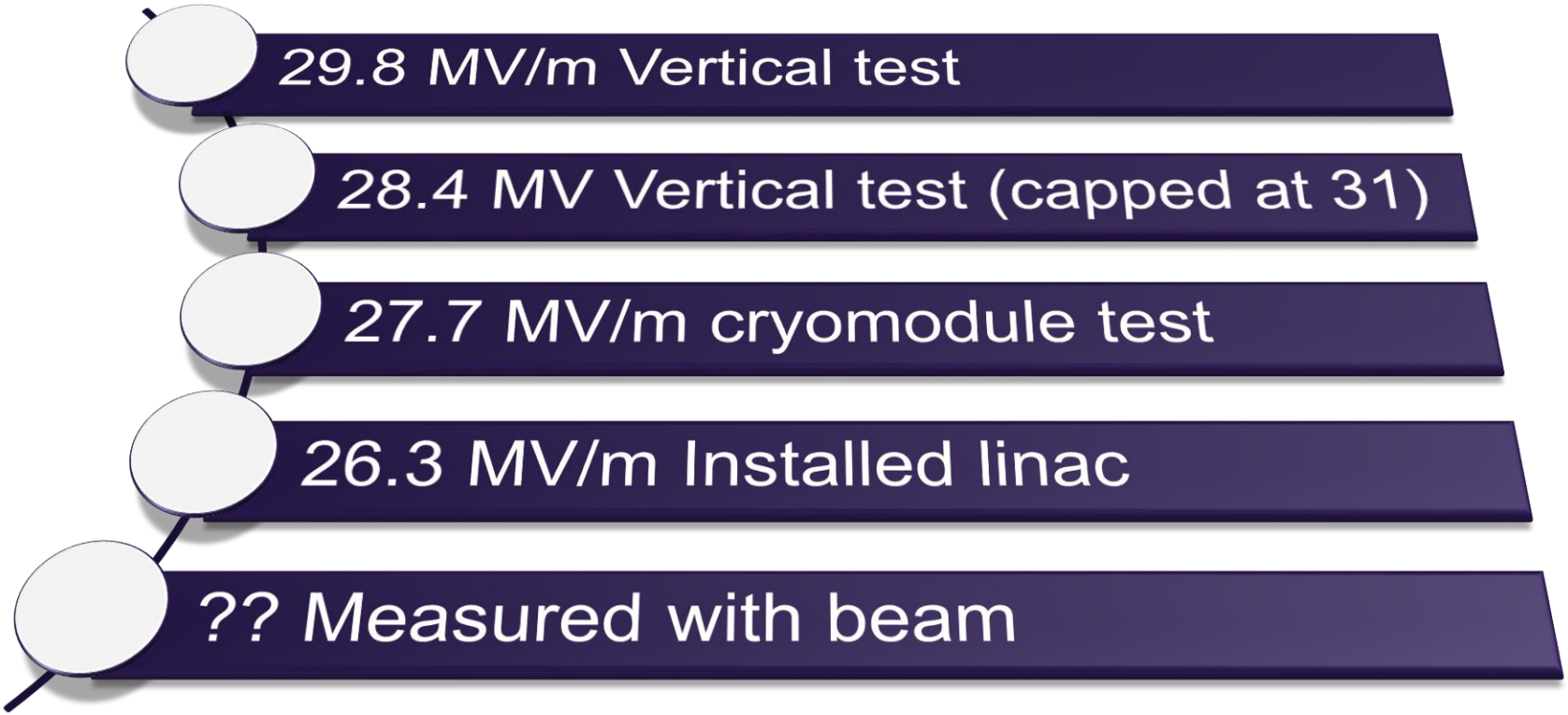


14% margin at 17.5 GeV

last RF station not installed (4 cryomodules)

European XFEL

Average gradient summary



Coming soon End of 2016!

Thanks to all colleagues of:

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