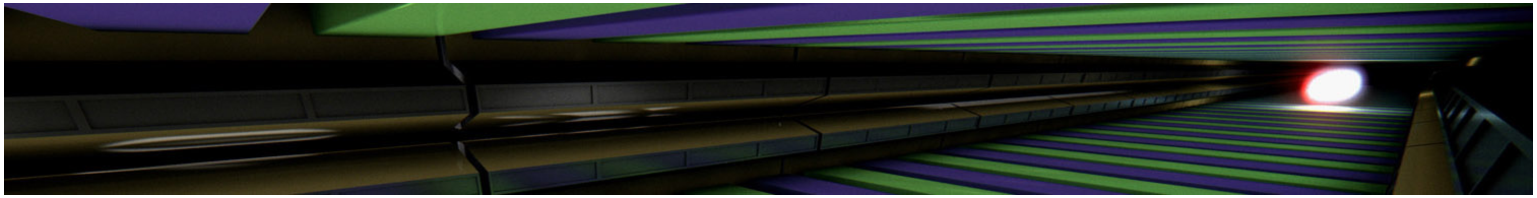
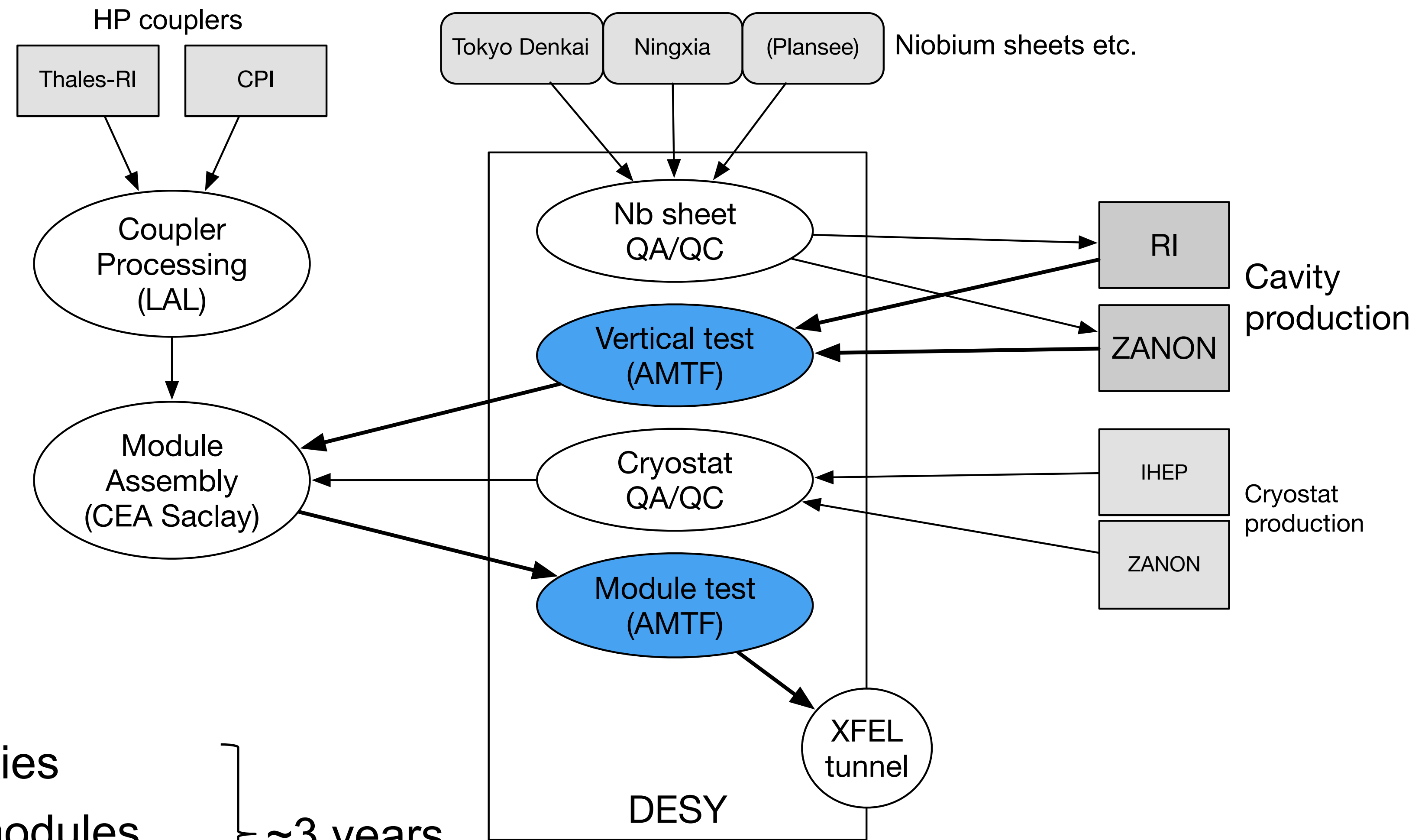


European XFEL, lessons learned, a stepping stone to a linear collider

Nick Walker (DESY)
for the XFEL team

GARD SRF 2017 workshop, FNAL, 9.02.17

Process overview



>800 cavities

103 cryomodules

98 installed in XFEL

~3 years

Cavity Production (EZ, RI)

Entirely produced by industry and delivered “ready to go”

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Lesson learned #1: Yes you can do this and it worked really well

Cavity Production (EZ, RI)

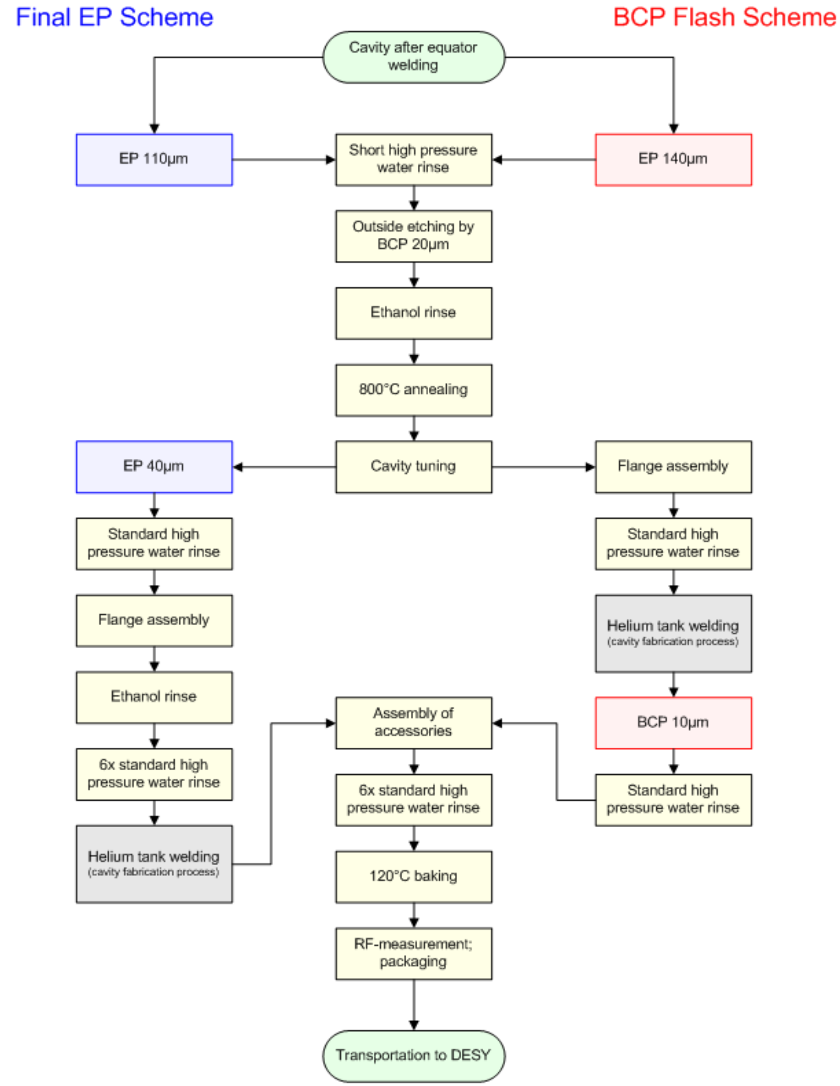
Entirely produced by industry and delivered "ready to go"

Lesson learned #1: Yes you can do this and it worked really well

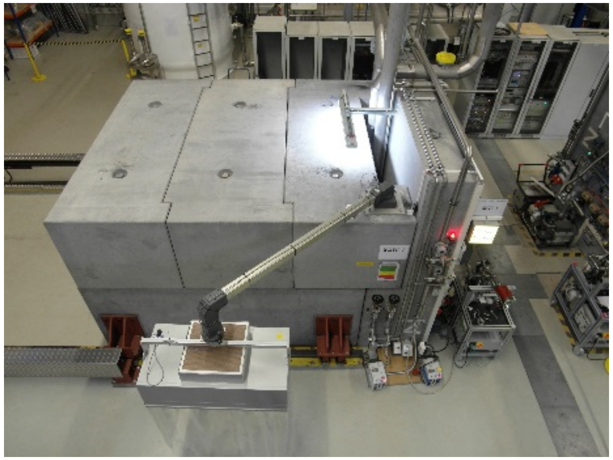
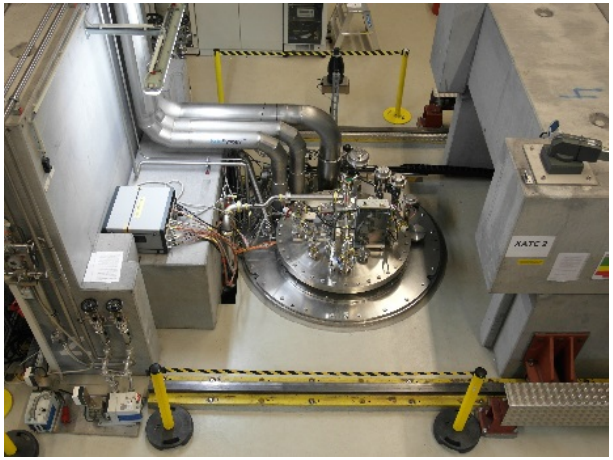
Lesson learned #2: Be prepared to invest a lot of effort into making it work

Cavity surface preparation

- Well-established process
  - >15 years R&D
- Two 'final' surface preparation methods:
  - RI: Final EP
  - EZ: Flash BCP
  - Vendor decision
- ILC TDR baseline is Final EP

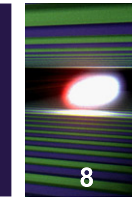


Vertical tests at AMTF

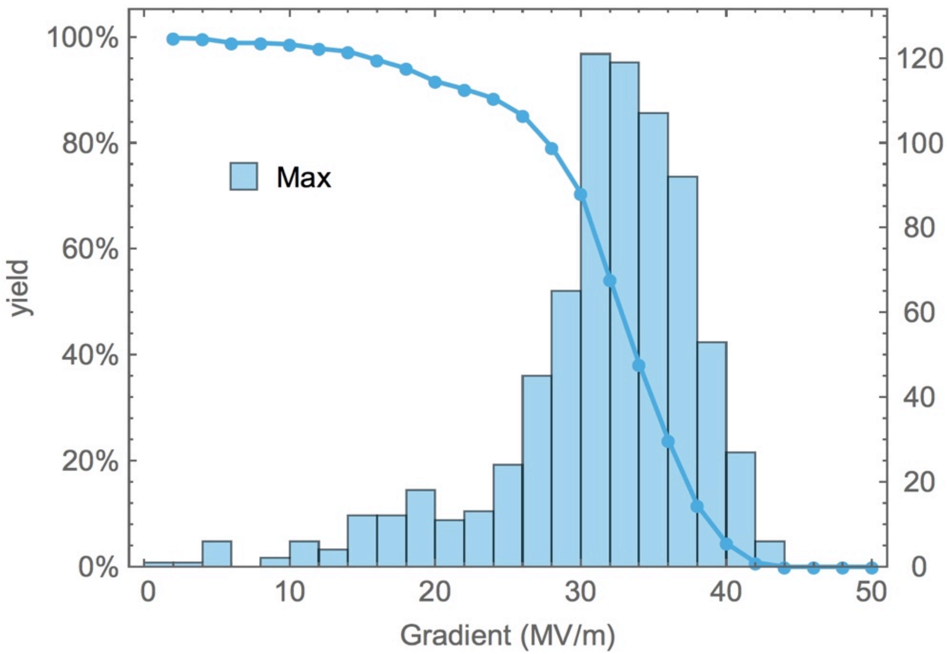



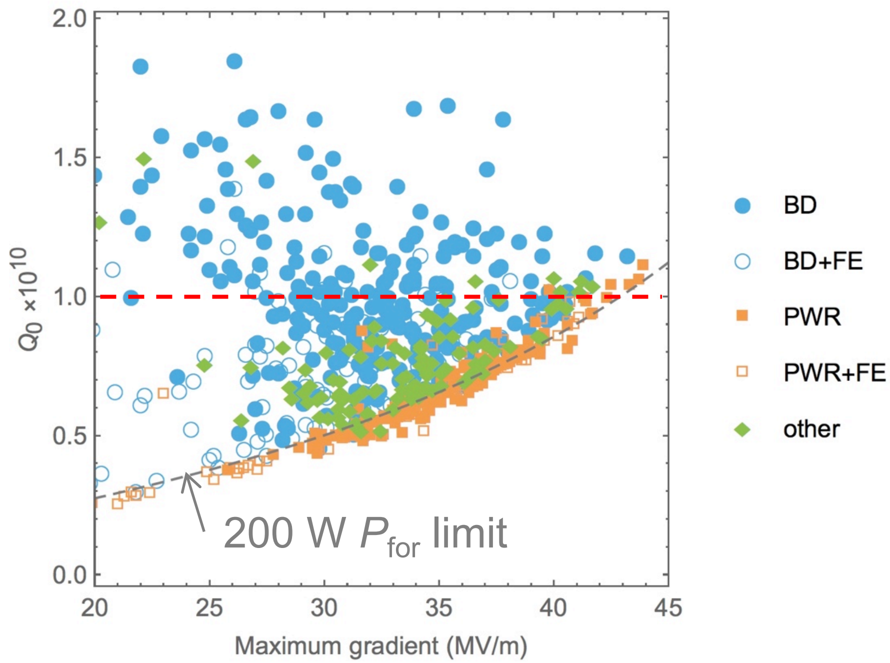


As Received Maximum Gradient in the VT

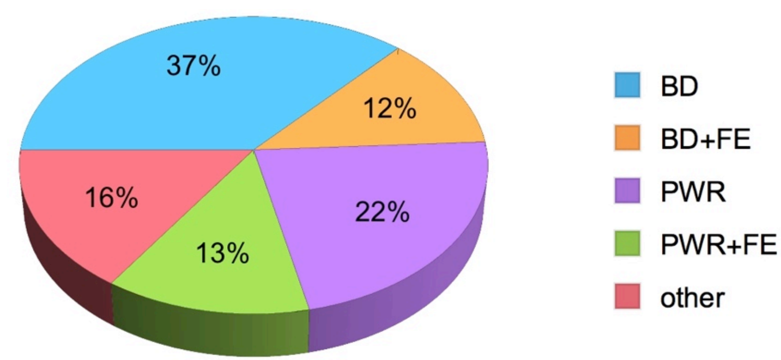


typical individual error: 10%



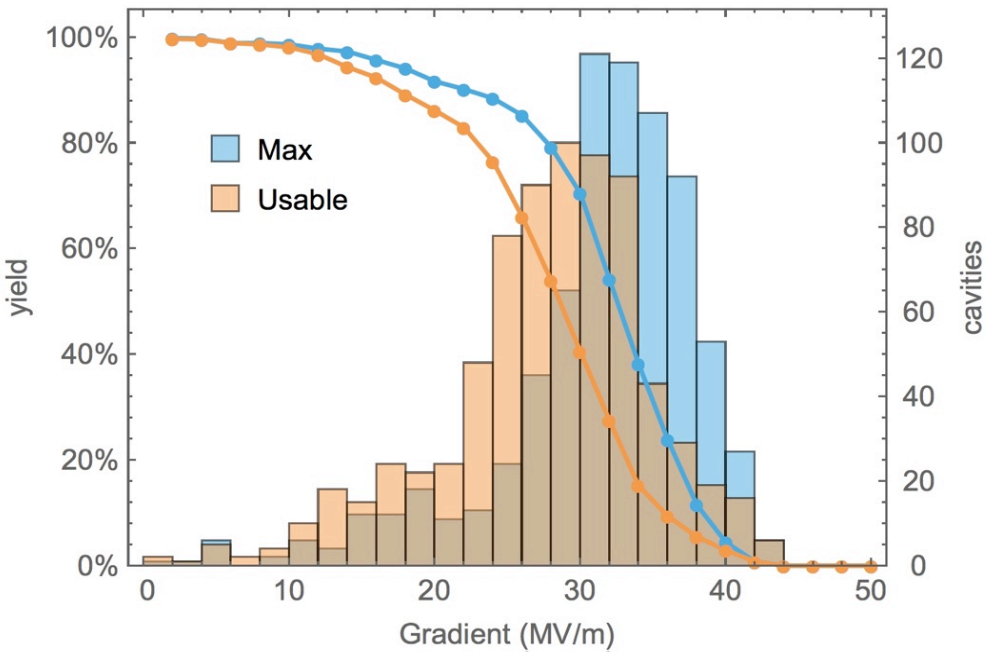


	Max
Number of cavities	745
⟨G⟩ [MV/m]	31.4
σ_G [MV/m]	6.8
$\langle G\rangle_{G\geq 28}$ [MV/m]	34.1
Yield @20	92%
Yield @28	79%
Yield @35	31%



As Received Usable Gradient in the VT

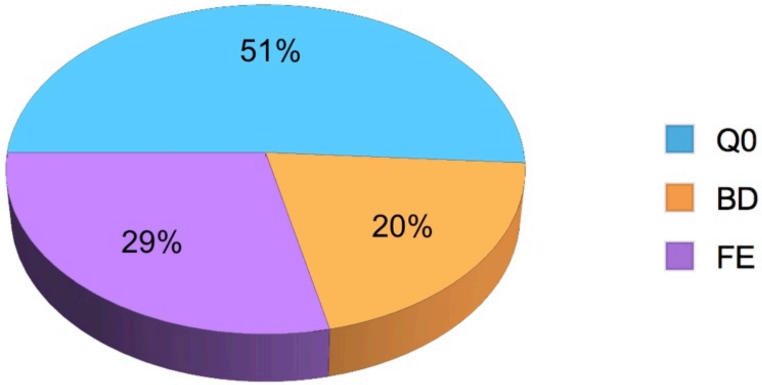
typical individual error: 10%



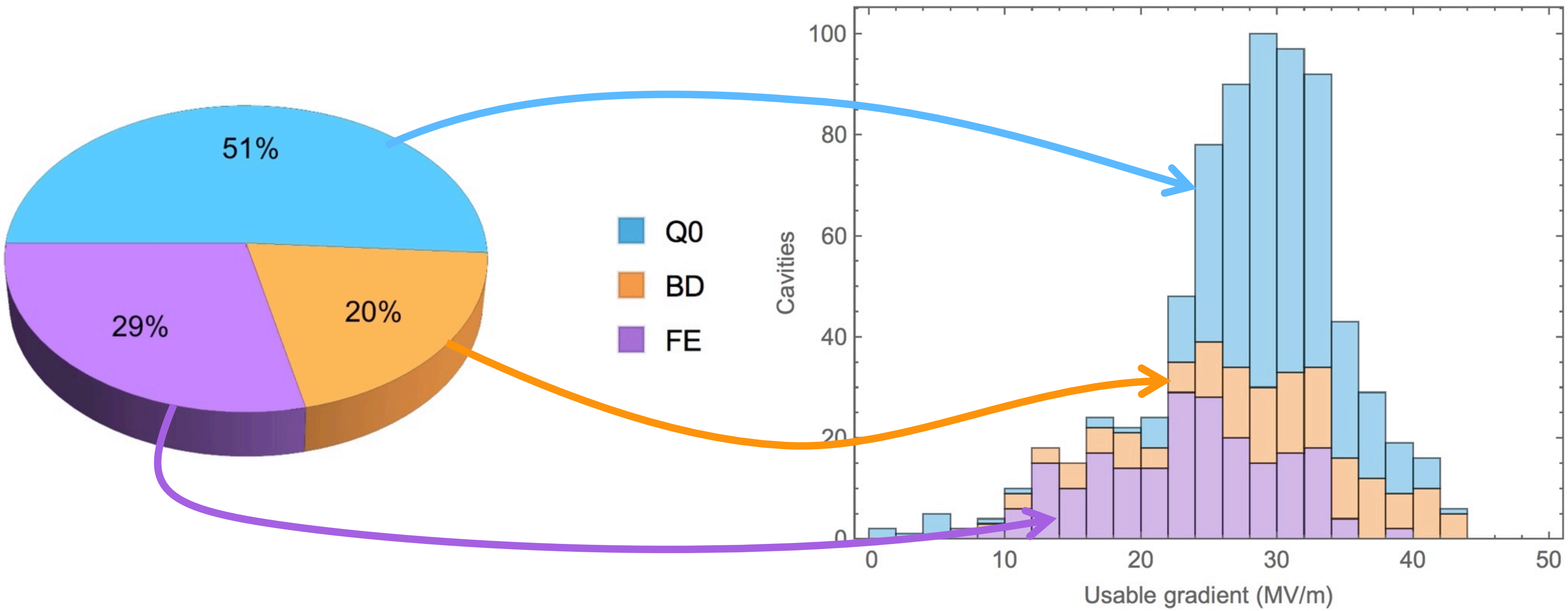
	Max	Usable
Number of cavities	745	745
⟨G⟩ [MV/m]	31.4	27.7
σ_G [MV/m]	6.8	7.2
$\langle G \rangle_{G\geq 28}$ [MV/m]	34.1	32.8
Yield @20	92%	86%
Yield @28	79%	54%
Yield @35	31%	12%

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

→ Usable Gradient



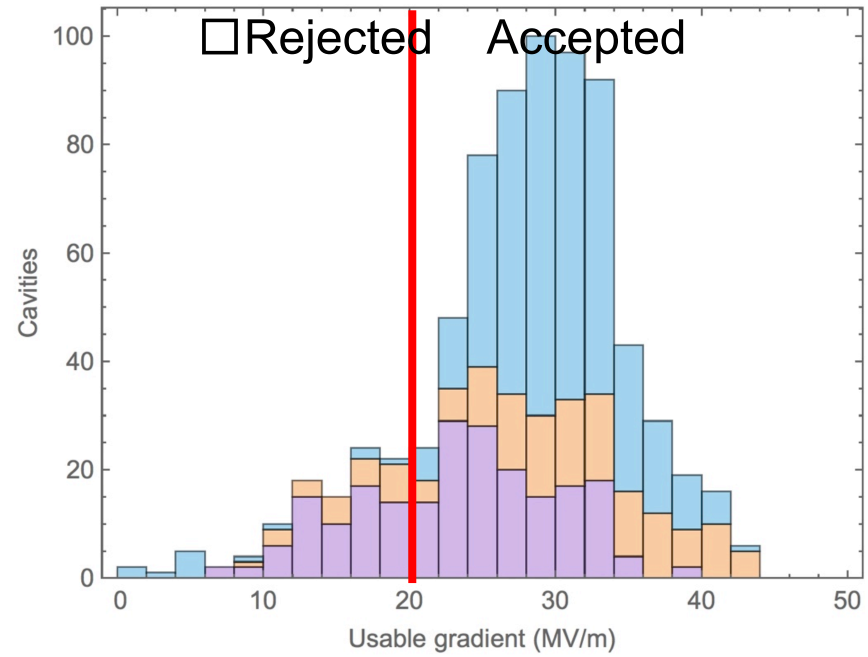
Usable gradient: limiting effects

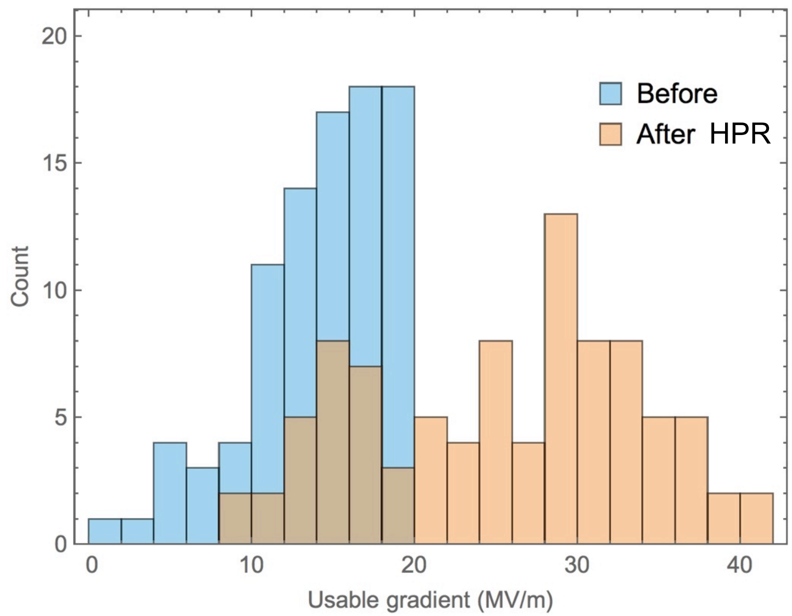


- Q_0 dominates at higher gradients (high-gradient Q-slope)
- Field Emission (FE) dominates <24 MV/m
- Quench (BD) not dominant –mostly higher gradients

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"

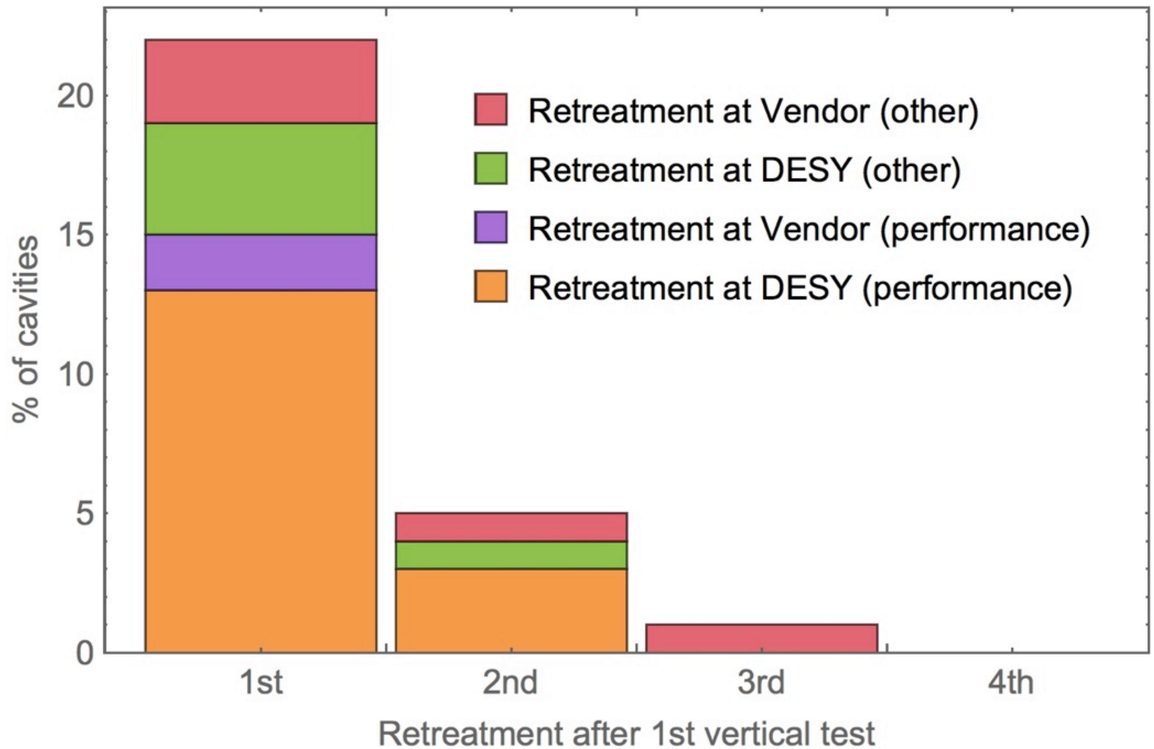




		Max	Usable
Average	MV/m	31.4	27.7
RMS	MV/m	6.8	7.2
Median (50%)	MV/m	32.5	28.7
Yield ≥20 MV/m		92%	86%
Yield ≥26 MV/m		85%	66%

Number of retreatments after the 1st vertical test

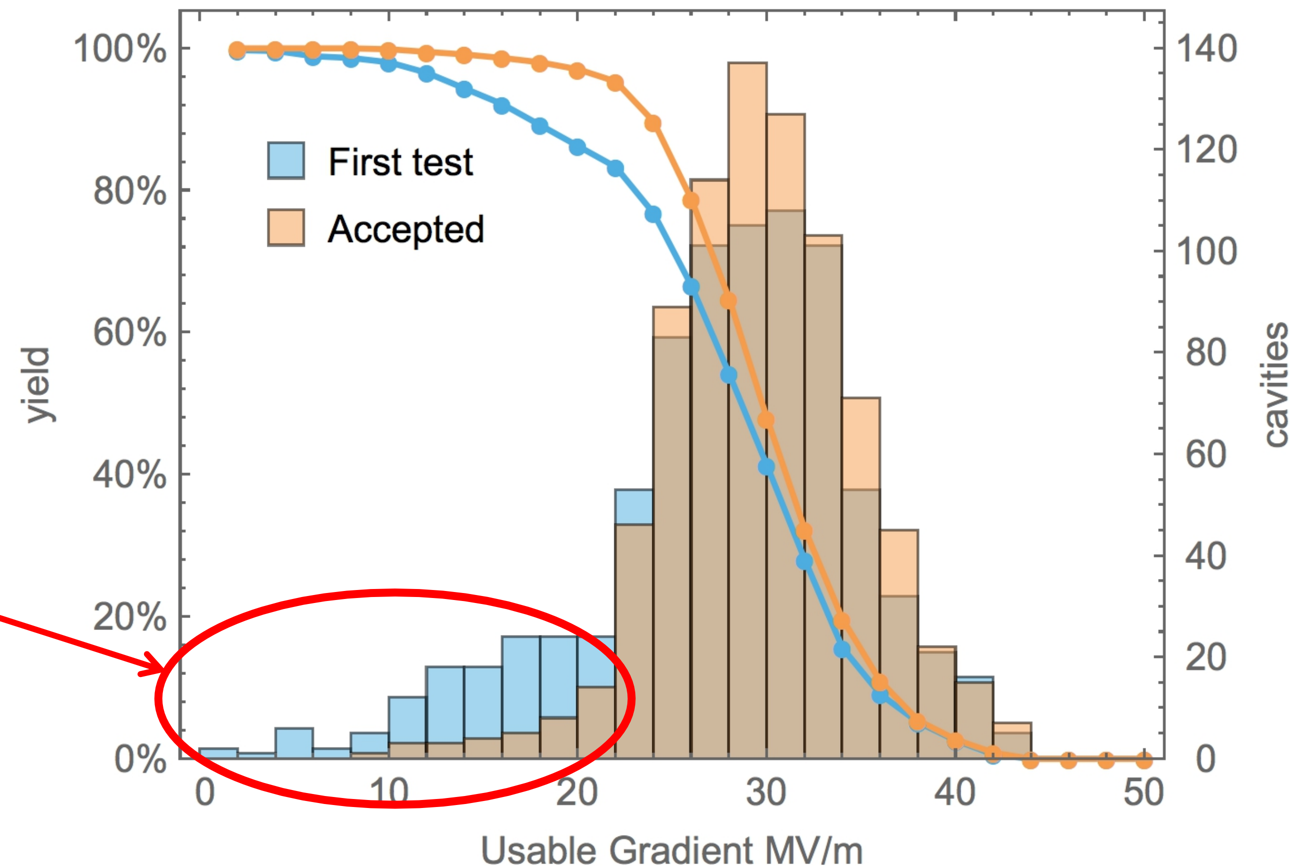
- Approx. 22% of cavities had ≥1 retreatment
  - ~15% performance-driven
  - ~7% due to vacuum- and mechanical-related problems (mostly HPR)
- 5% had 2 or more retreatments.
  - including both chemical and mechanical (grinding)



Final performance (sent for module assembly)

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

impact of retreatment



European XFEL

As received Q_0 performance

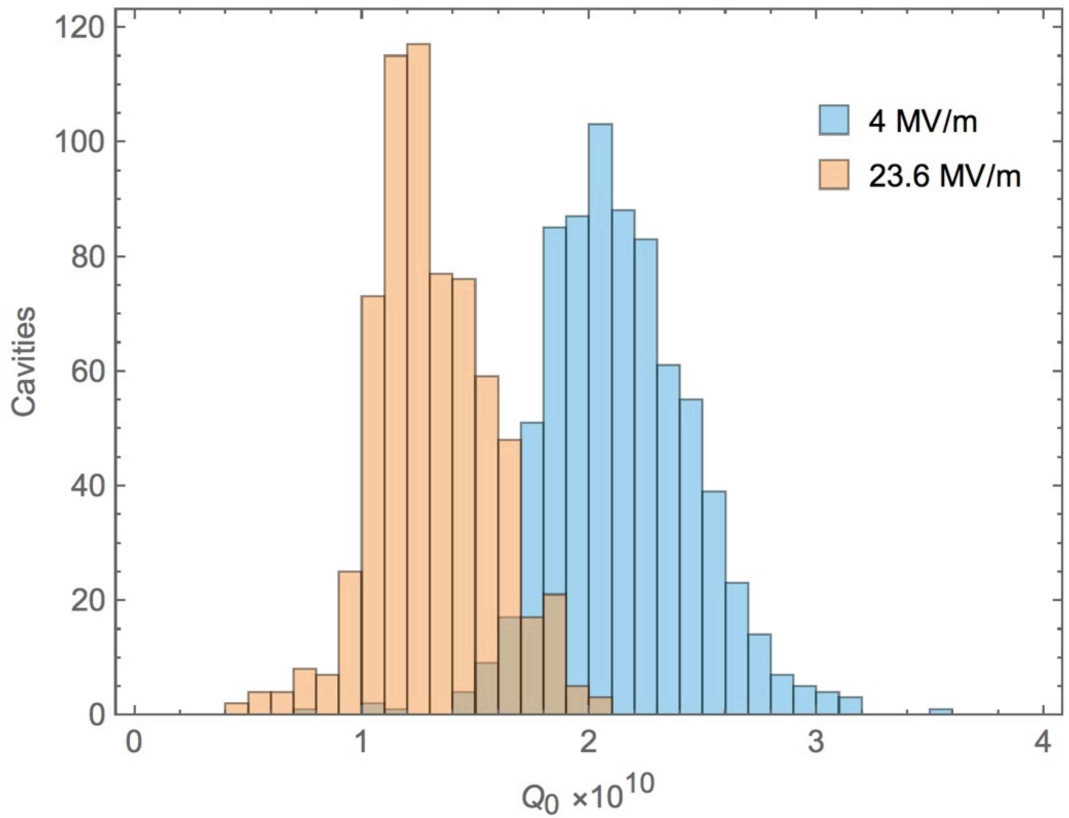
Average ±RMS:

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

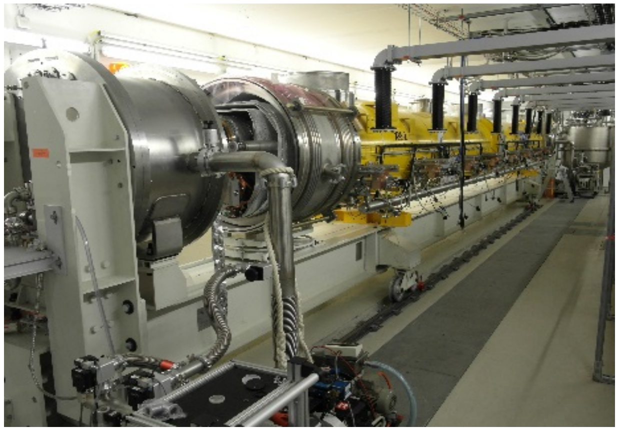
23.6 MV/m: $1.3 \pm 0.3 \times 10^{10}$

Estimated measurement error 10-20%

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



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

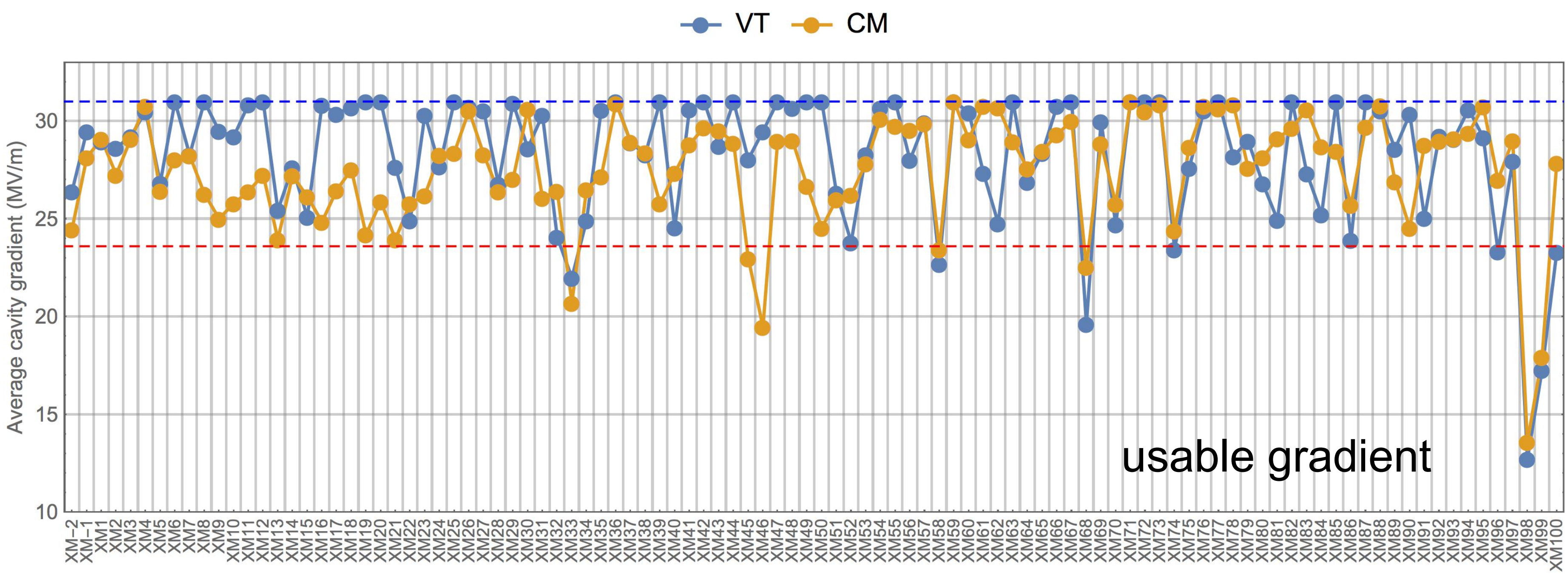
VT vs MT: Making Comparisons

	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	… 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

Cryomodule average gradient performance



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

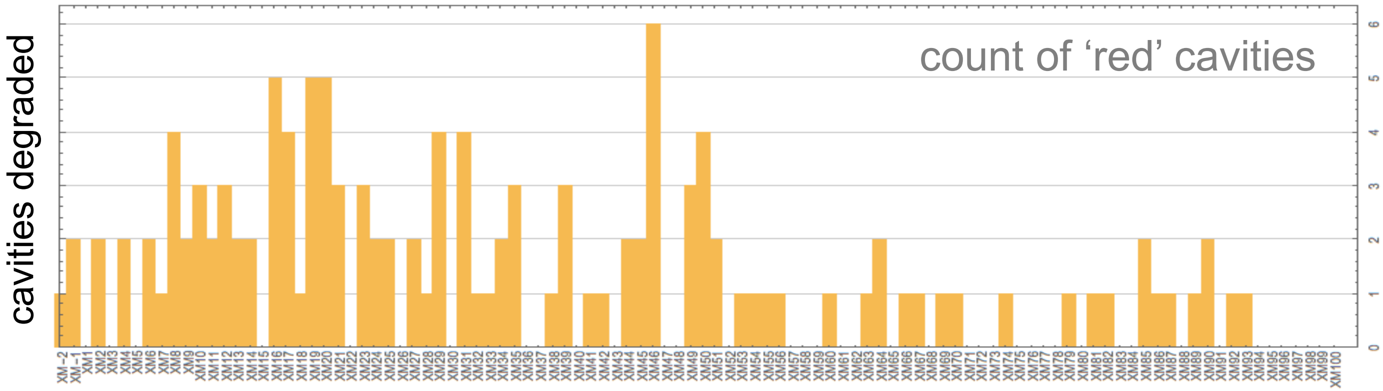
VT capped at 31 MV/m for fair comparison

~3% difference measured this way

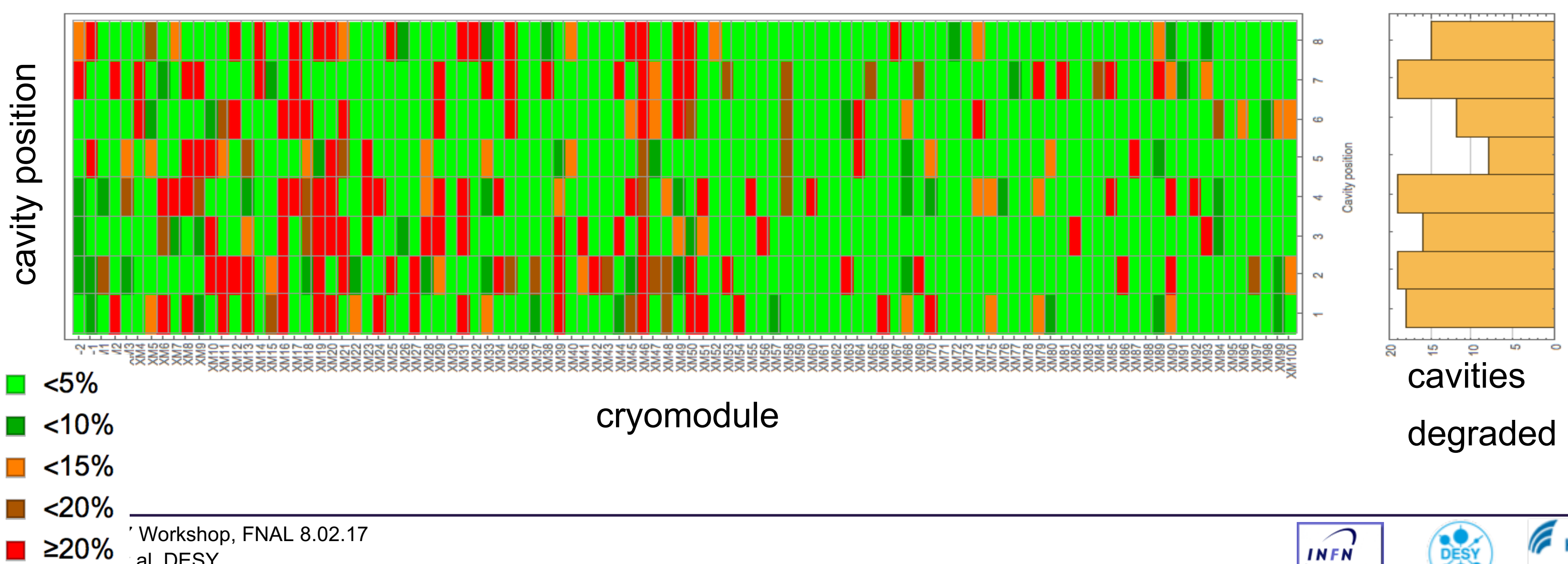
3% ≤ ΔG ≤ 8%

Degradation matrix

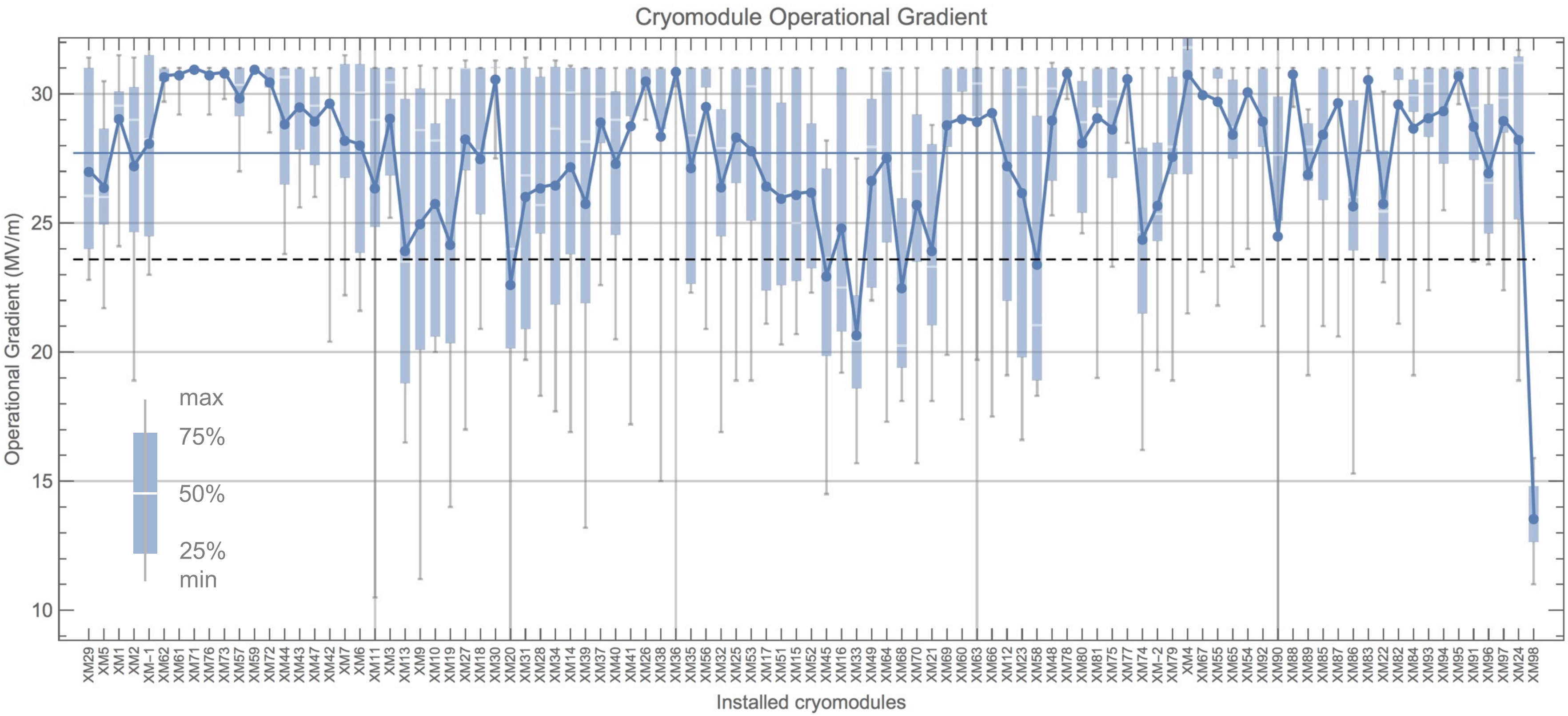
Degradation defined as ≥20% (red)



best place to be a happy cavity in a cryomodule



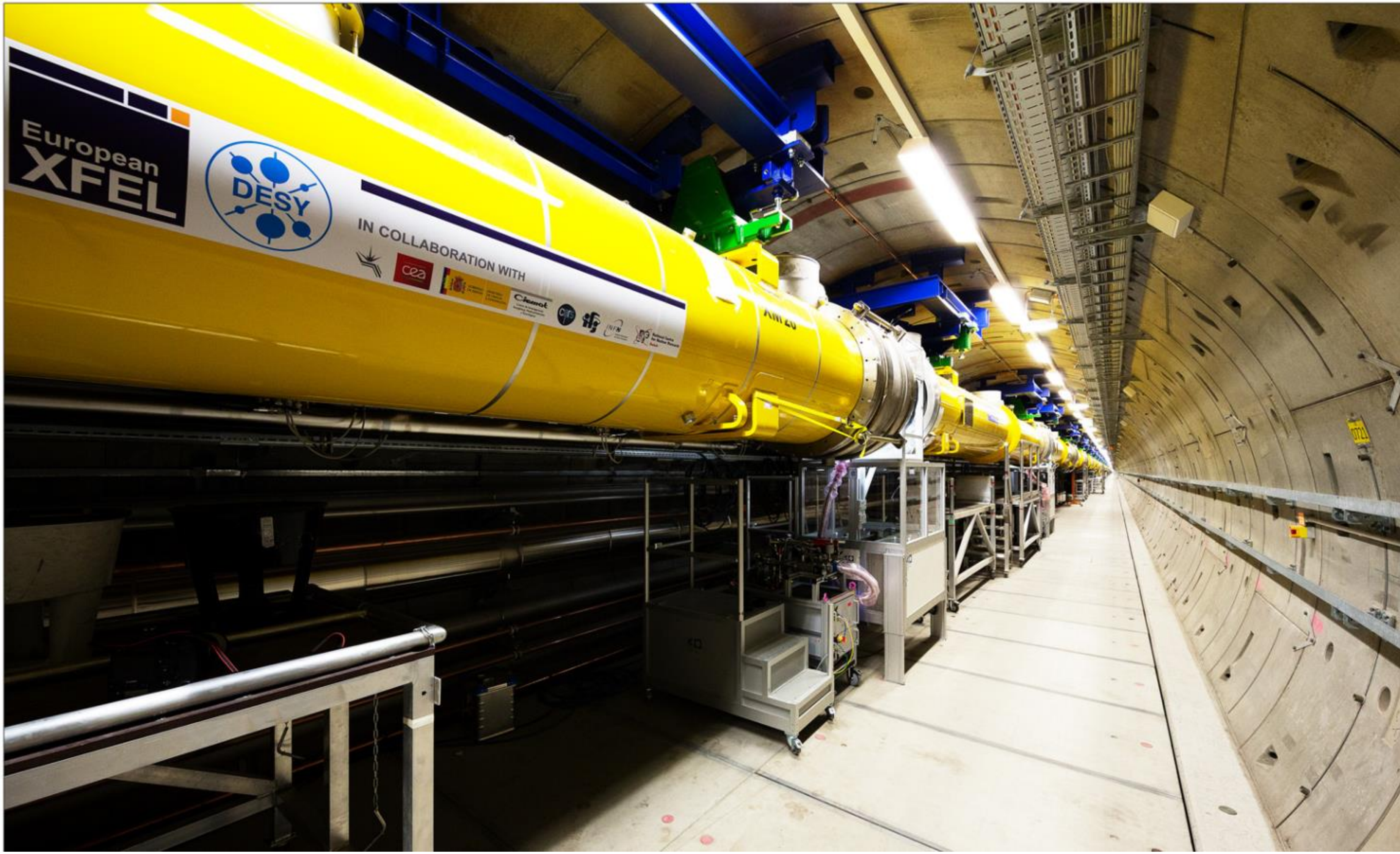
Cryomodule performance (AMTF module test)



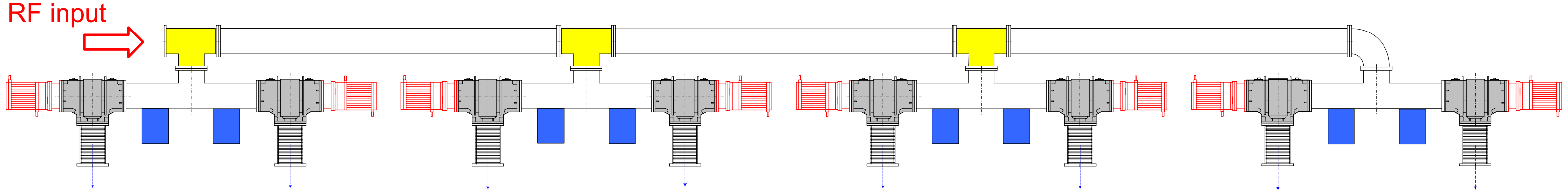
Average (blue line) is good but spread within modules is still quite large

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

Into the LINAC

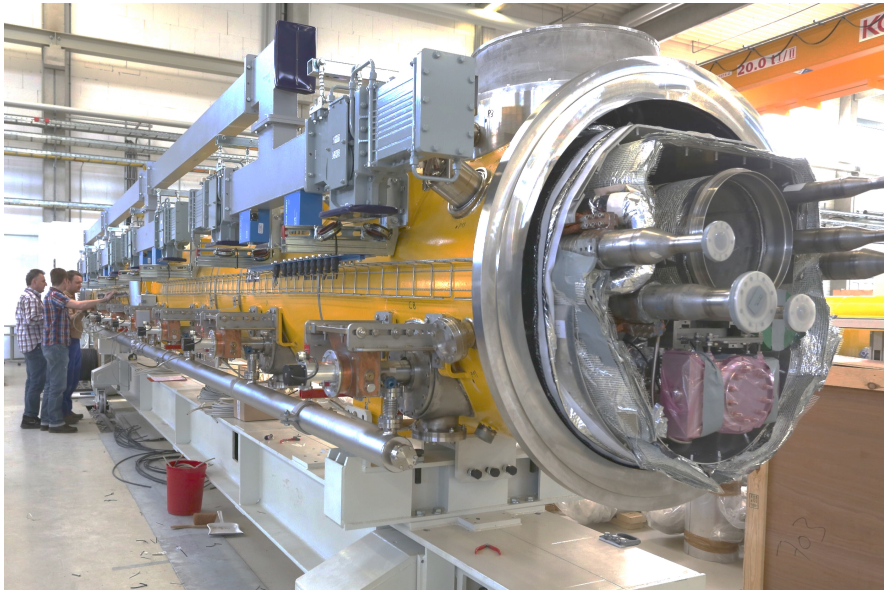


Impact of Waveguide Distribution (WD) system (Installed Gradient)



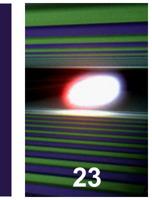
courtesy V. Katelev

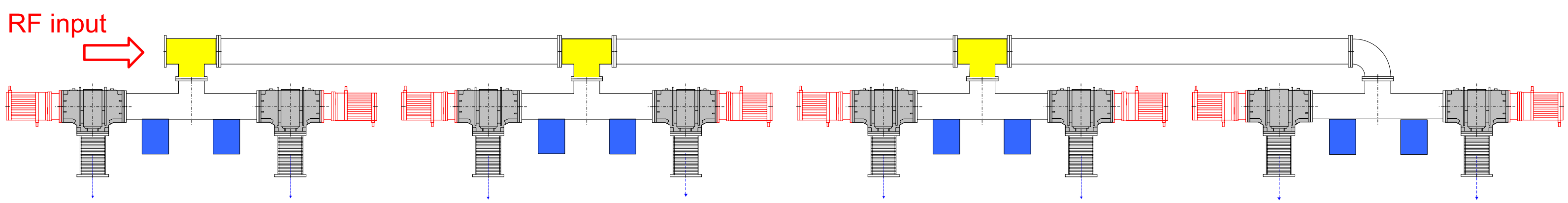
- 1 10-MW klystron drives four modules (32 cavities)
- WD for cryomodules tailored for MT results
  - maximising voltage
  - up to 3dB difference between cavity pairs
- Allow up to 3dB split between adjacent cryomodule pairs
- Equal power output from two klystron arms



see THPLR067 Choroba, Katalev, Apostolov

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





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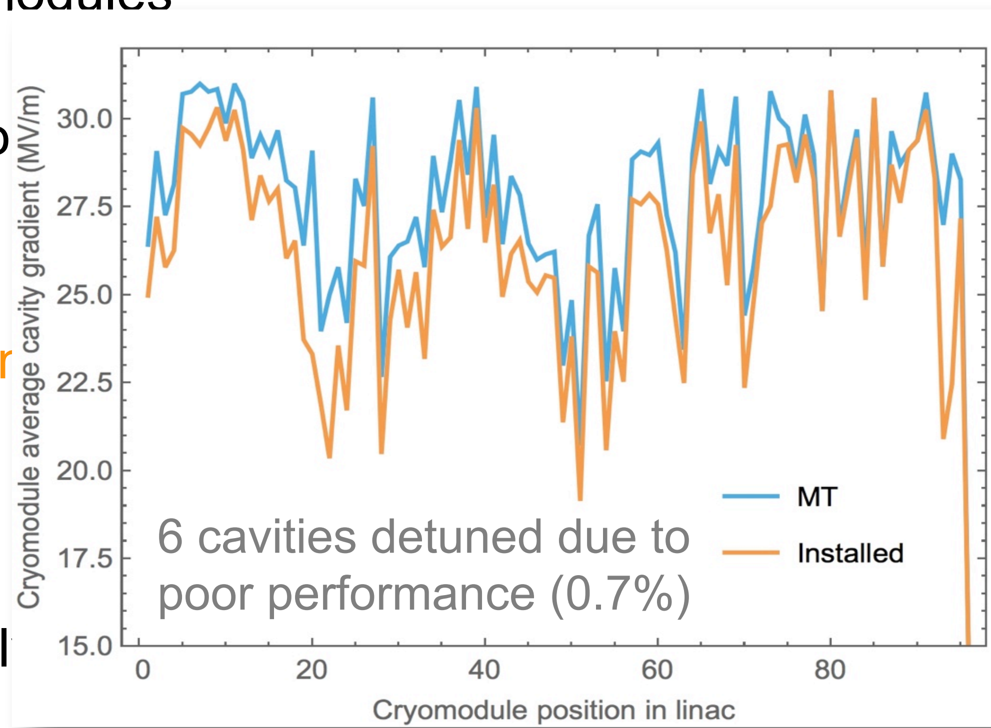
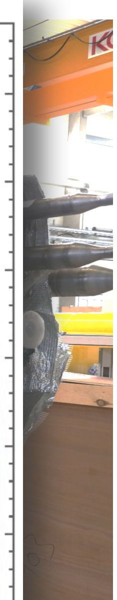
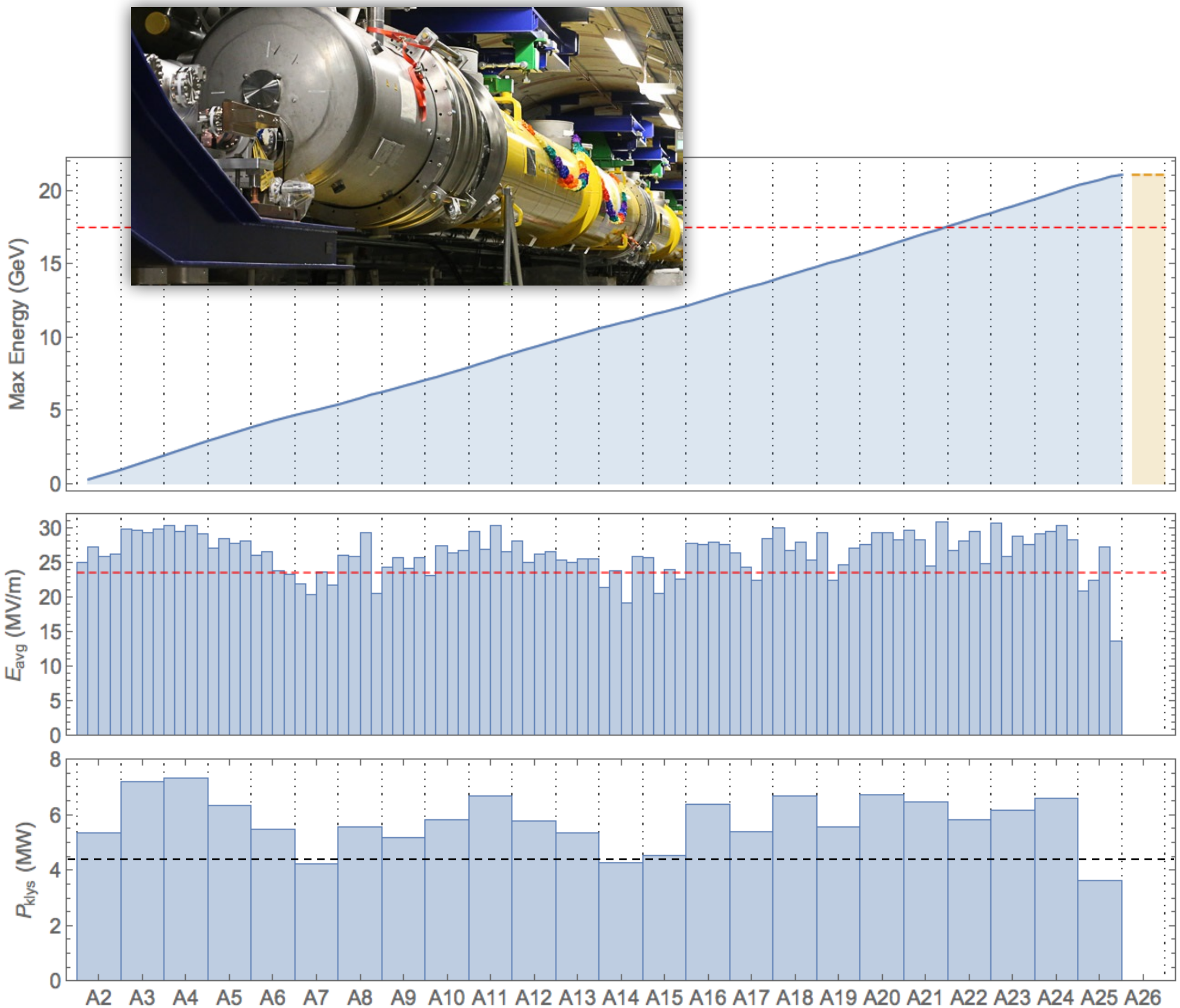




Projected installed energy profile



E_{max} ~ 20 GeV

17.5 GeV

14% margin at 17.5 GeV

23.6 MV/m

4.3 MW

last RF station not installed (4 cryomodules)

ILC specifications

Has XFEL achieved them?

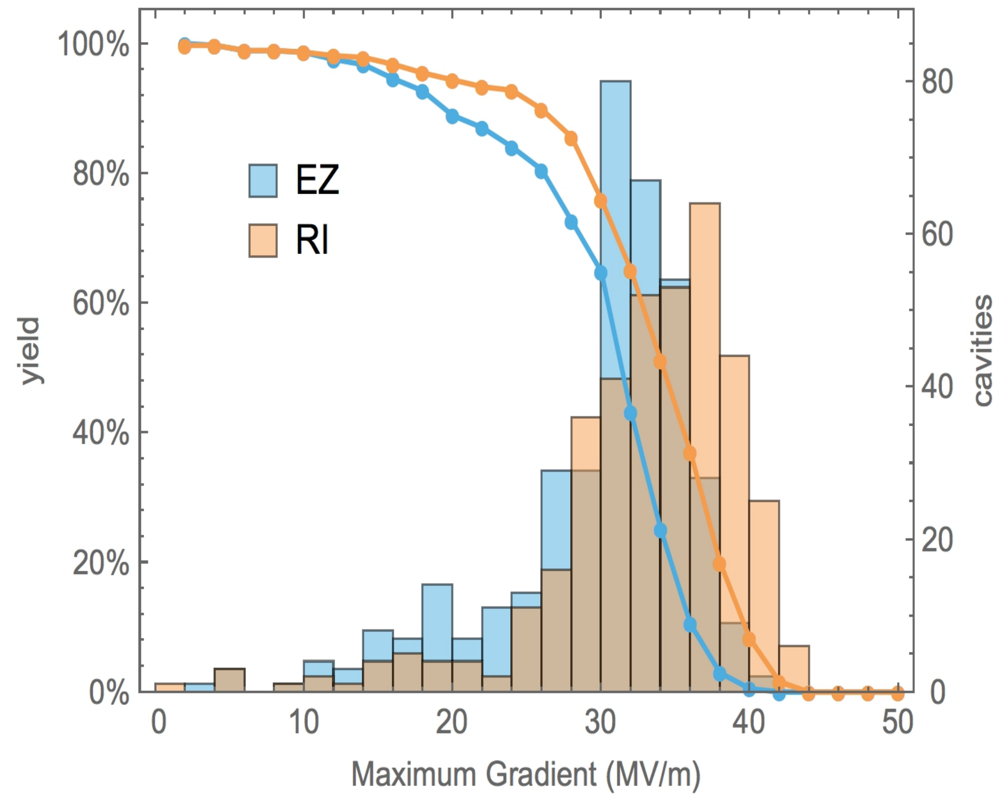
(Discussing mostly VT performance)

ILC assumptions

- Vertical Test qualification
  - $\geq$ 35 MV/m with $Q_0 \geq 8\times10^9$
- Installed
  - $\geq$31.5 MV/m with $Q_0 \geq 10^{10}$ (10% for degradation and operations margin)
- Specification for gradient spread ±20%
  - 28 MV/m $\leq g \leq$ 42 MV/m, $\langle g \rangle$ = 35 MV/m
- Reinterpret VT Qualification as required *yield* $\geq$ 28 MV/m with $\langle g \rangle$ = 35 MV/m ($Q_0 \geq 10^{10}$?)
  - First pass: 75%
  - Second pass: 90%

} TDR cost model

'Final EP' vs 'Flash BCP'



RI (Final EP)

	Max	Usable
Number of cavities	375	375
⟨G⟩ [MV/m]	33.	29.
σ_G [MV/m]	6.6	7.4
$\langle G \rangle_{G \geq 28}$ [MV/m]	35.	33.3
Yield @20	94%	89%
Yield @28	86%	63%
Yield @35	44%	18%

- RI cavities showed ~10% improvement in average performance
  - Both max and usable
- Mostly attributed to high-field Q-slope associated with Flash BCP

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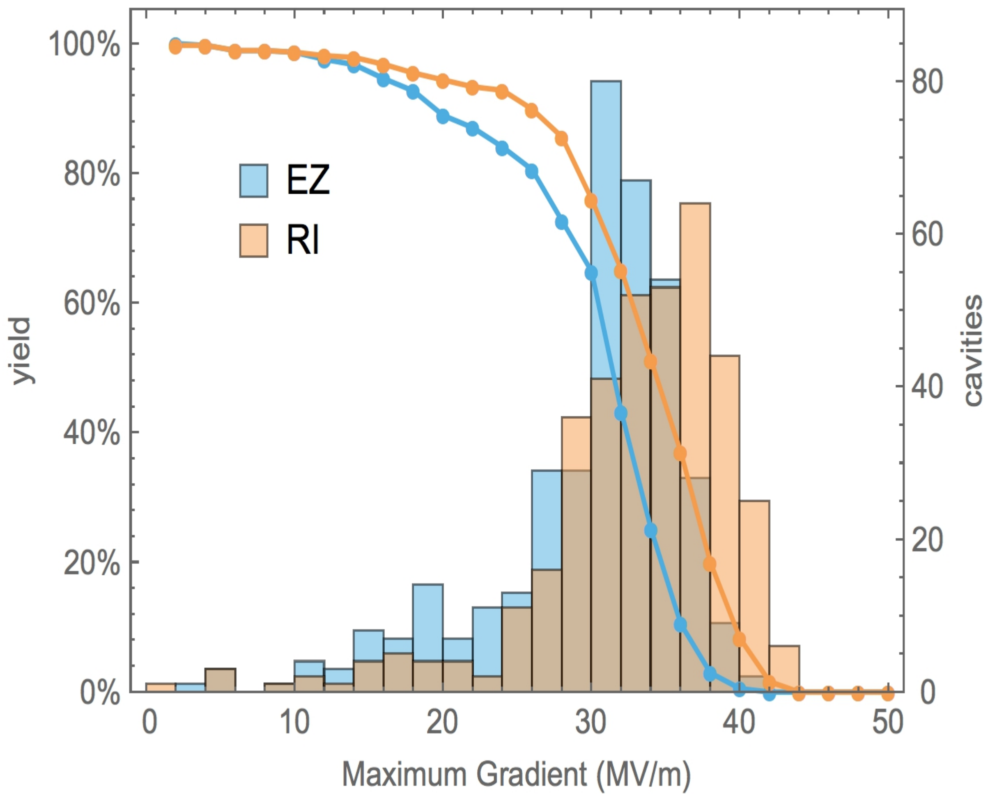

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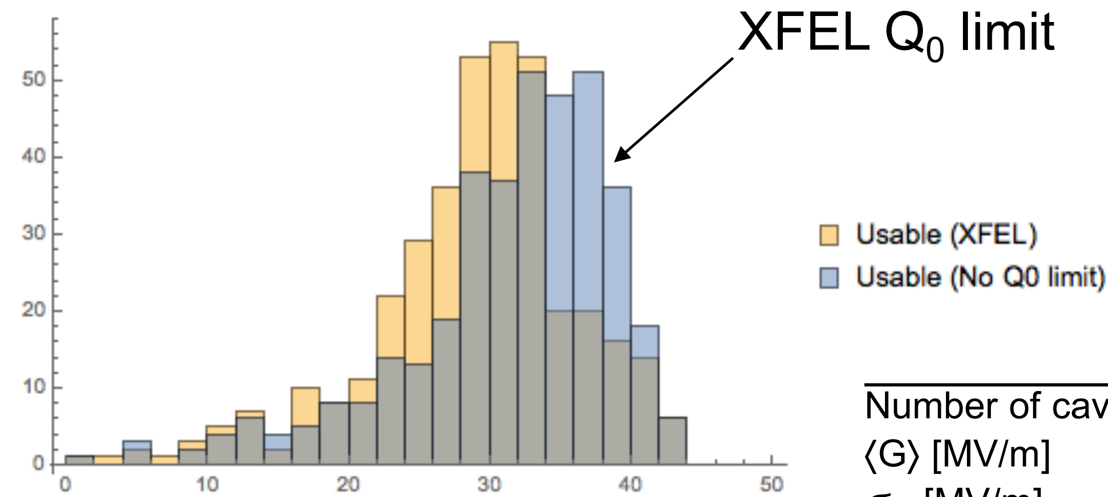
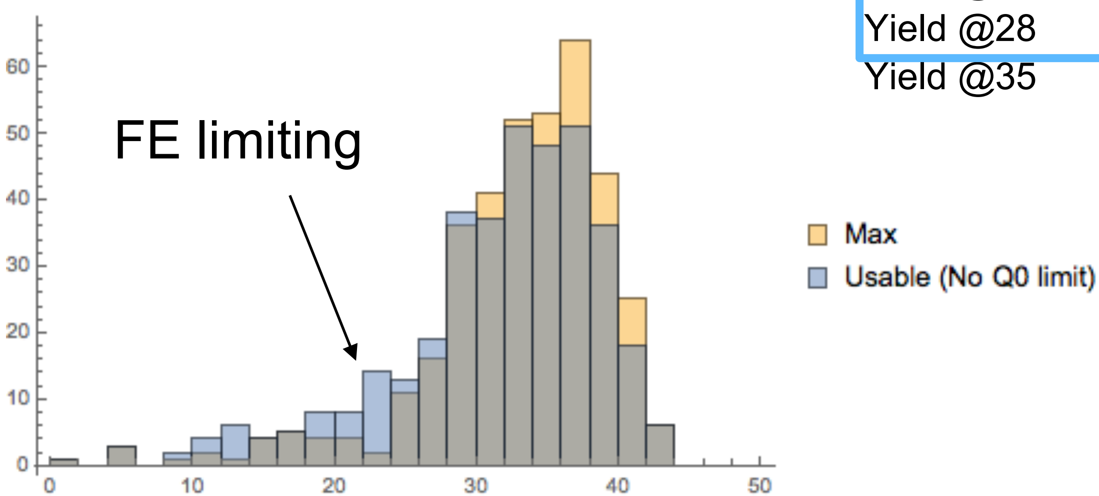
Usable field – ignore Q_0? (FE only)

RI cavities only



	Max	Usable	usable No Q
Number of cavities	375	375	372
⟨G⟩ [MV/m]	33.	29.	31.4
σ_G [MV/m]	6.6	7.4	7.5
$\langle G\rangle_{G\geq 28}$ [MV/m]	35.	33.3	34.7
Yield @20	94%	89%	91%
Yield @28	86%	63%	77%
Yield @35	44%	18%	37%

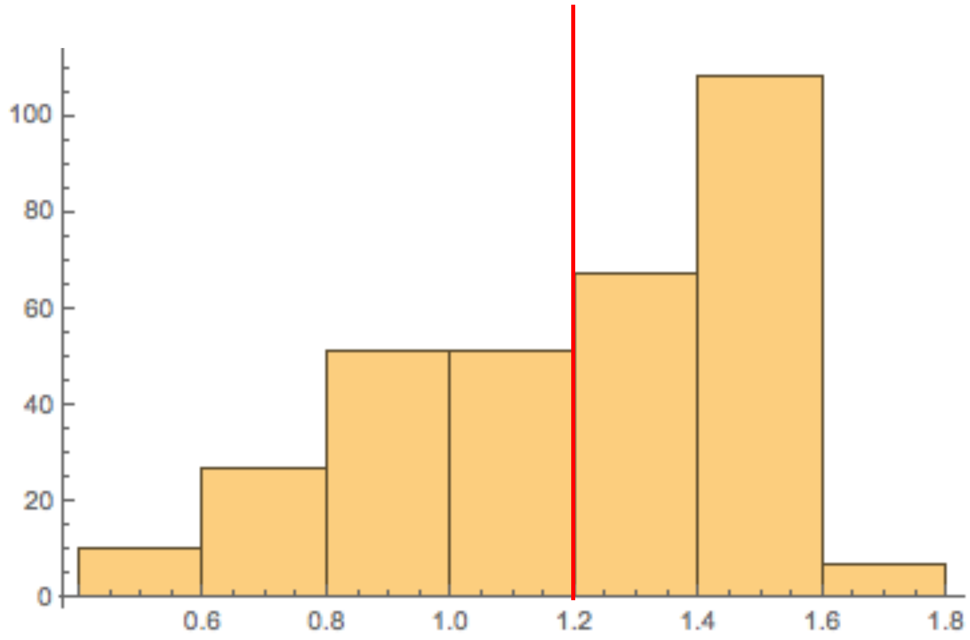


Cannot just ignore Q_0

Calculate g^2/Q_0 all cavities with g≥28 MV/m

Normalise to to $35^2/10^{10}$

Average 1.2



True first pass yield is between XFEL and ‘no Q_0’ limits (63% and 77%)

Second pass?

- No direct 'correct' comparison possible
  - Cut off for XFEL retreatment ≤20 MV/m
  - ILC is ≤28 MV/m
- Can try to use retreatment MC model based in XFEL results

		ILC TDR (assumed)	XFEL max	XFEL usable
First-pass	Yield >28 MV/m Average >28 MV/m	75% 35 MV/m	85% 35.2 MV/m	63% 33.5 MV/m
First+Second pass	Yield >28 MV/m Average >28 MV/m	90% 35 MV/m	94% 35.0 MV/m	82% 33.4 MV/m
First+Second+third pass	Yield >28 MV/m Average >28 MV/m	- -		91% 33.4 MV/m

More re-treatments - but mostly only HPR

Number of average tests/cavity increases from 1.25 to 1.55 (1st+2nd) or 20% over-production or additional re-treat/test cycles

European XFEL

Lessons Learnt?

- TESLA technology has been successfully industrialised and can be mass produced
  - No reasons why this cannot be extrapolated to ILC numbers
- Success requires DILIGENCE (and attention to detail)
  - Close cooperation with cavity vendors
  - Constant feedback, QA and QC
- Standard 'TESLA' recipe can *almost* achieve ILC specifications
  - But improvement still needed
  - 30 MV/m average is great by 7 MV/m RMS spread is too large (why?)
  - Q_0 performance (Nitrogen anybody?)
- String assembly without degradation is not impossible
  - Again, requires diligence!
  - Auditing, QA/QC, feedback, etc.