Industrial fabrication and surface treatment of superconducting RF cavities: challenge and main lesson

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INFN - LASA

Talk outline

- Strategies for large number of cavities production
- Consideration on large number of cavities production
    - The E-XFEL cavities production
        - Preparation phase
        - Technology transfer
        - Qualification of new infrastructures at industries
        - Series production
    - LCLSII
        - Recipe definition
        - Preparation phase
        - Results
- Main lesson: what we have learned?

Cavities' general fabrication scheme

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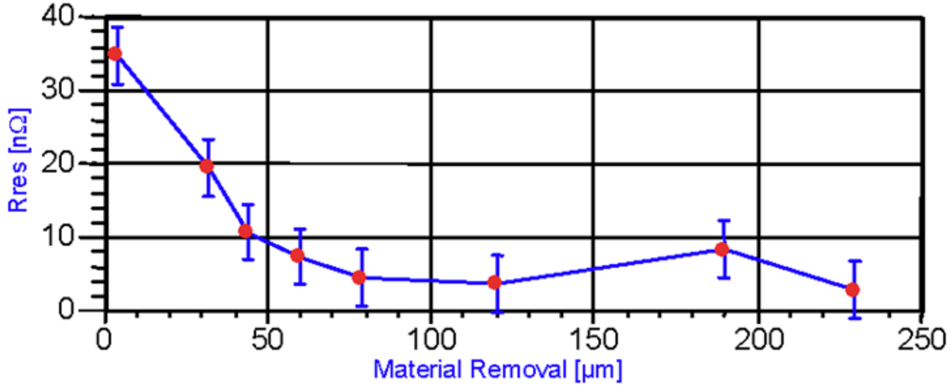
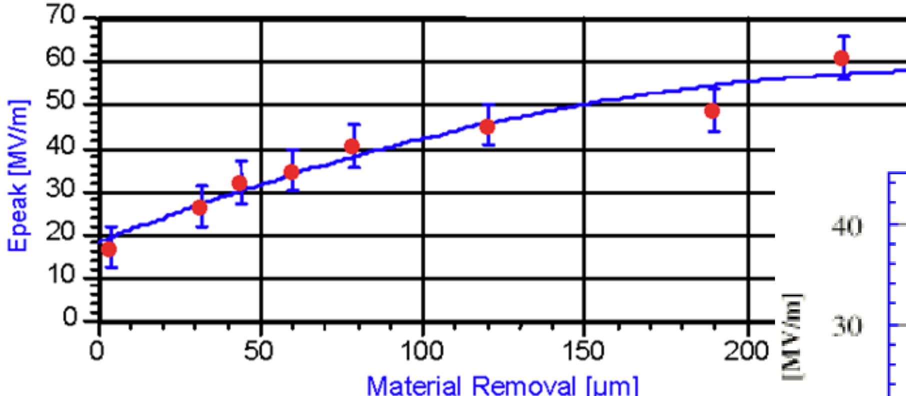
Step	WHY	COMMENTS
Forming		
EB Welding	Clean welding	Nb = getter material. If RRR/ 10 @ welding => $Q_0/10$
Ti purification	RRR enhancement	RRR 300-400 now commercially available
Chemical etching 100-200 µm (BCP / EP)	Remove contamination and damage layer	Limitation : BCP ~ 30MV/m; EP => >40 mV/m but lack of reproducibility
Annealing 800°C, 2h (or 600°C, 10h)	Get rid of hydrogen	Source of H: wet processes H segregates near surface in form of hydrides (= bad SC)
Chemical etching 5-20 µm	Remove diffusion layer (O, C, N)	Diffusion layer < ~1µm in bulk, a little higher at Grain Boundaries
Specific rinsing	e.g. remove S particles due to EP	Under evaluation HF, H_2O_2, ethanol, degreasing,…
High pressure rinsing (HPR)	Get rid of dust particles	Not always enough (recontamination during assembly)
Assembling	Ancillaries : antennas, couplers , vacuum ports…	**In clean room, but recontamination still possible**
Baking, 120°C, 48h	Decrease high field losses (Q-drop)	Unknown mechanism, first 10 nm of the surface in concern.
Post processing	Get rid of "re-contamination" ?	Under evaluation: dry ice cleaning, plasma
Test RF	Cavity's performance	First naked cavity in vertical cryostat, then dressed in horizontal cryostat/ accelerating facility
He processing, HPP	Decrease field emission	RF power with/ without He to destroy field emitters (dust particles) NB field emission : principal practical problem in accelerators

Prepare inner surface for the RF field

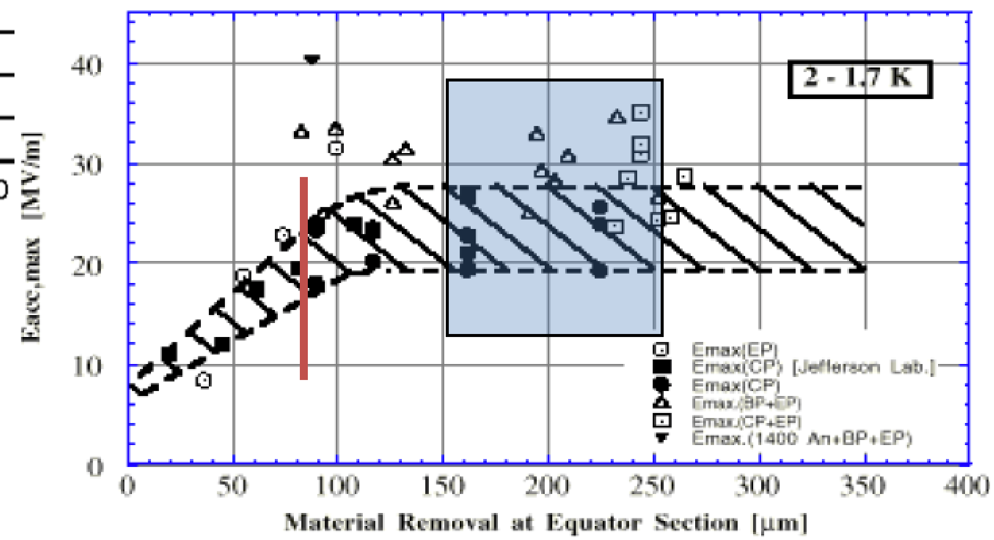
- After deep drawing, EBW and other machining, a removal of the Nb damaged layer **(150 – 200 µm)** is needed.





P. Kneisel

K. Saito



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Strategy for series cavity production (1)

"In House" cavity production strategy

Laboratory	Industry
Cavity design	
Material qualification and buying	
Prototype development	
Surface treatment	
Prototype testing	
Detailed specification available	
Series production (mechanical)	
Series production surface treatments	
Cavities testing	
Cavities installation in cryomodules	
Cryomodule testing	

Strategy for series cavity production (2)

"Hybrid" cavity production strategy

Laboratory	Industry
Cavity design	
Material qualification and buying	
Prototype development	
Surface treatment	
Prototype testing	
Detailed specification available	
	Series production (mechanical)
Series production surface treatments	
Cavities testing	
Cavities installation in cryomodules	
Cryomodule testing	

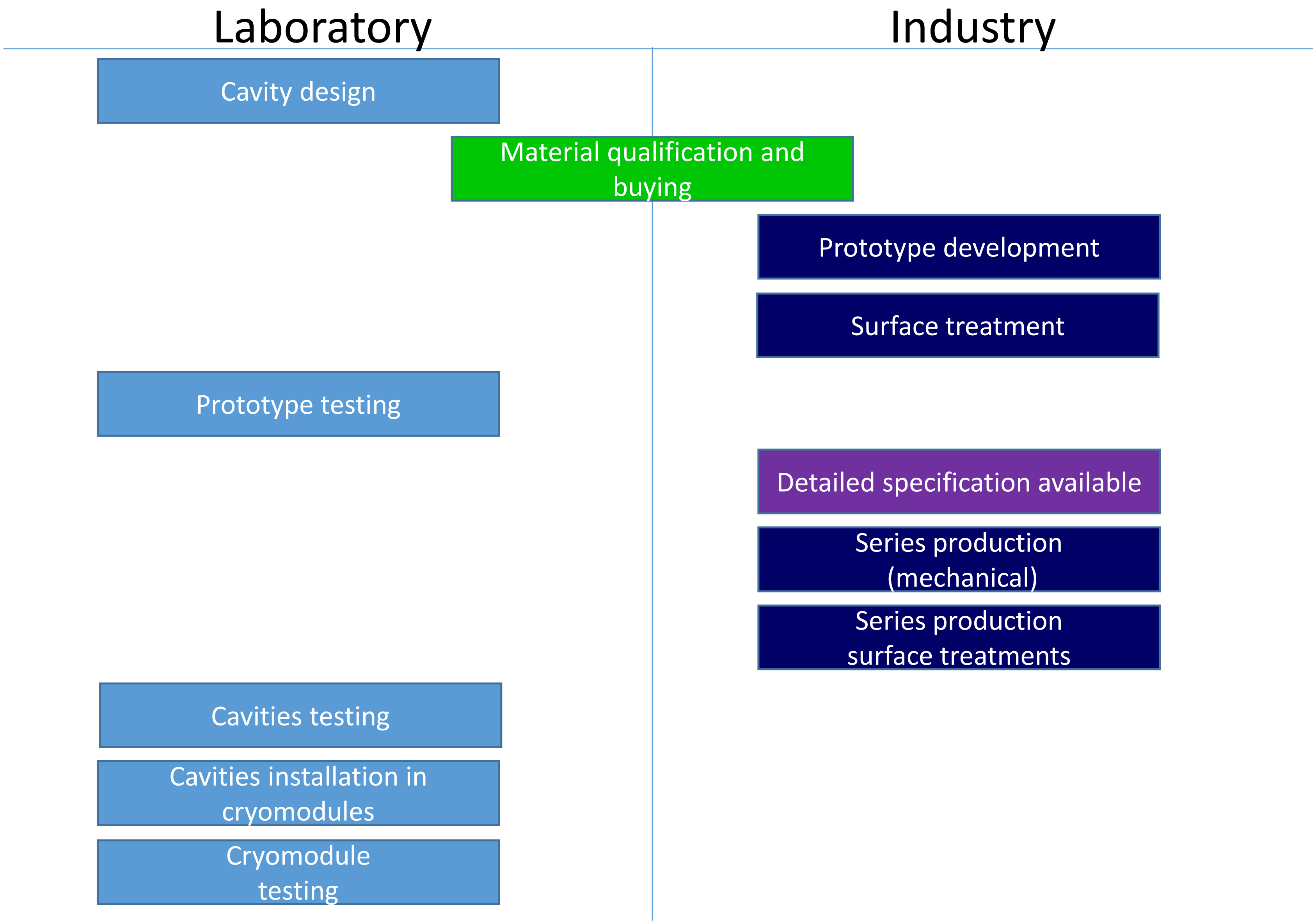
Strategy for series cavity production (3)

"Built to print" cavity production strategy

Laboratory	Industry
Cavity design	
Material qualification and buying	
Prototype development	
Surface treatment	
Prototype testing	
Detailed specification available	Detailed specification available
	Series production (mechanical)
	Series production surface treatments
Cavities testing	
Cavities installation in cryomodules	
Cryomodule testing	

Strategy for series cavity production (4)

“Fully industrial” cavity production strategy



Strategy for series cavity production (5.1)

“Fully industrial” cavity production & module assembly strategy

Laboratory	Industry
Cavity design	
Material qualification and buying	Material qualification and buying
	Prototype development
	Surface treatment
Prototype testing	
	Detailed specification available
	Series production (mechanical)
	Series production surface treatments
Cavities testing	
	Cavities installation in cryomodules
Cryomodule testing	

Strategy for series cavity production (5.2)

“Fully industrial” cavity production & module assembly strategy

Laboratory	Industry
Cavity design	
Material qualification and buying	Material qualification and buying
	Prototype development
	Surface treatment
Prototype testing	
	Detailed specification available
	Series production (mechanical)
	Series production surface treatments
Cavities testing	
	Cavities installation in cryomodules
Cryomodule testing	

100 % test?

Strategy for series cavity production (5.3)

"Fully industrial" cavity production & module assembly strategy

Laboratory	Industry
Cavity design	
Material qualification and buying	Material qualification and buying
	Prototype development
	Surface treatment
Prototype testing	
	Detailed specification available
	Series production (mechanical)
	Series production surface treatments
Cavities testing **100 % test?**	
	Cavities installation in cryomodules
Cryomodule testing **100 % test?**	

Large projects: huge number of cavities

Reason for industrialization

- **Large projects** require a **huge number** of cavities and a **massive number of high quality Nb sheets** and components.
- **Laboratories resources couldn't be able** to manage large number of cavities with enough quality, man power, optimized cost, scheduling respect, etc.
- High production rate: **order of some cavities/week**
- **Series production**: needs process optimization, not always part of the lab knowhow
- **Extremely high quality control** is a **must** due to the high number of cavities.
- **Cavity design** and its related feasibility have to be verified /optimized for **series production**

Large scale cavities production critical aspects

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- **Debugged and solid recipe is a must**: no R&D feasible during industrial production. **Risk for delays.**
- Usually **long production cycle**.
  From EBW to final steps (E-XFEL): **3 months**.
- **Large number** of cavities **involved in the production cycle**, i.e. in different production phases.
- **Long time delay for any feedback** from cavity testing to the production system.
  - **Risk for several defective cavities** production and a **long and expensive recovery process.**
  - **To reduce the risk, intermediate diagnostics tools must be set up**, as optical inspections, Residual Gas Analysis (RGA) during pumpdown, etc.
  - **Preventive maintenance** on plants to mitigate possible faults.
- **Cavity design** must foresees for possible **repairing actions** on the cavity (i.e. tank removal for a new bulk surface treatment).

Extremely high quality control a the production site is a must!

E-XFEL Cavity Production Overview

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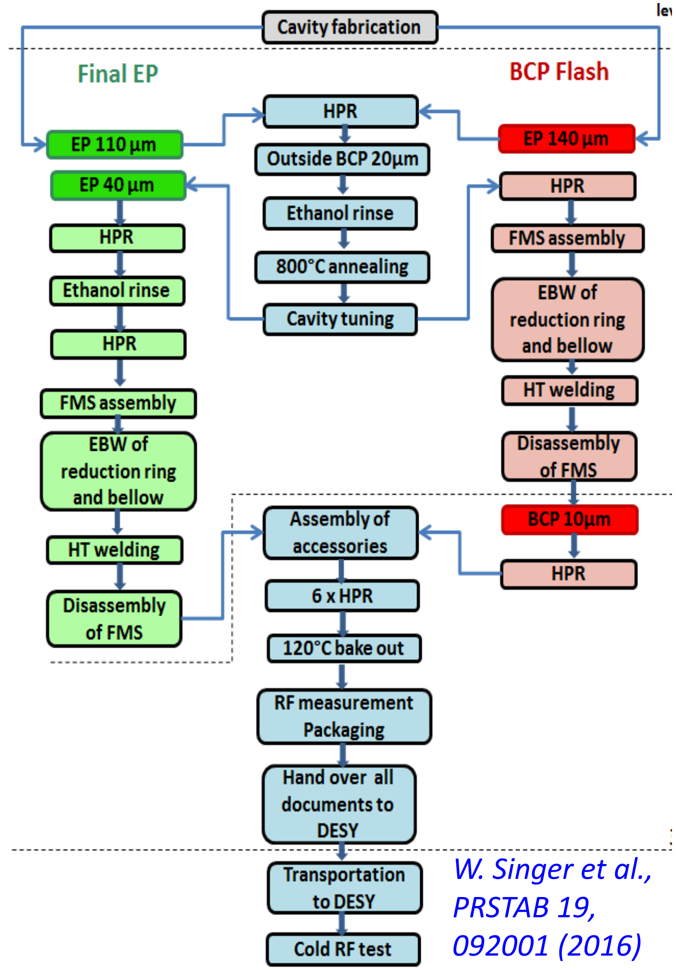
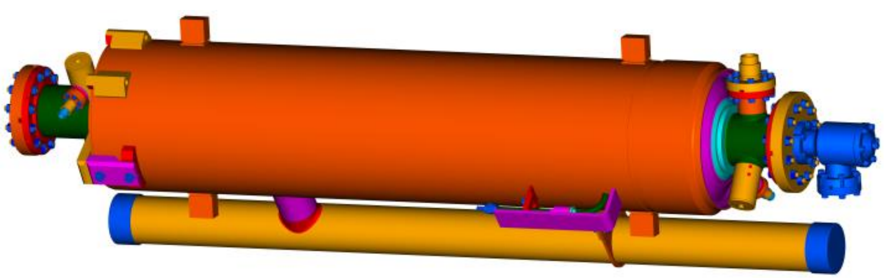
- **Two Companies** committed for the 400 + 400 1.3GHz cavities production: **E. Zanon (EZ) & Research Instruments (RI)**
- Two recipes (choice left to the Companies):
- **Flash BCP** & **Final EP**
  - **EZ applied the Flash BCP**
  - **RI applied the Final EP**
- **Strategy: Built to Print** (**no performance guaranteed!**) for the first time applied on a large scale cavity production
- **Full procedure** (from the raw material to the cavity ready to be tested) **done at the Industry** (mechanical, RF, surface treatments, vacuum, etc)



W. Singer et al., PRSTAB 19, 092001 (2016)

- **Recovery of cavity** with poor performance -> responsibility of **DESY / INFN**



E-XFEL strategy for series cavities production

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- The **build to print strategy** was chosen for procurements of XFEL SC cavities. Production has to **follow precisely** the in detail worked out **specifications** which also **include the exact definition of infrastructure to be used.**
- **Two companies** commissioned for **risk reduction.**
- **No performance guaranteed** by the vendors (possibly re-treatment at DESY or at the company)
- **Goal: average usable gradient E_{acc}= 23.6 MV/m (Q_0=1x10^{10}, X-Rays <1x10^{-2} mGy/min)**
- Delivery rate: **8 CVs/week** (2 companies)

- **Supervision of Cavity production**: **DESY + INFN-LASA**

From Lab to the Industry for E-XFEL cavities

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- **Material** and vendor qualification for Nb
- Cavity **design qualification**
- **Surface treatment** qualification
- Cavity producer **qualification**: mechanical fabrication
- Procurement of Nb and semi- finished parts
- **Definition** of the "external" QA/QC for the company
- **PED issue analysis** (E-XFEL is cat. IV!, modul B + F)

Preparatory phase
Laboratory level

- **Technology Transfer to the companies for series cavities production**
- **Set up of infrastructures**
- **Qualification** of the transferred technology: DCV e RCV
- Set up of the **external QA/QC** system at the industry
- **Series cavities** production: continuous monitoring of key parameters

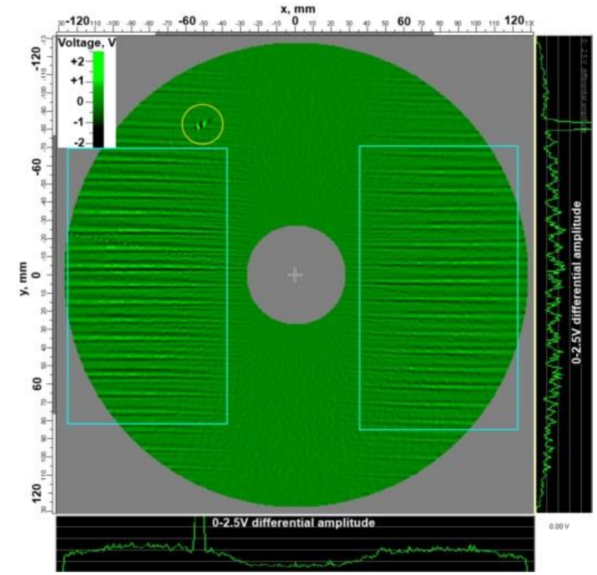
Series production
Industry level

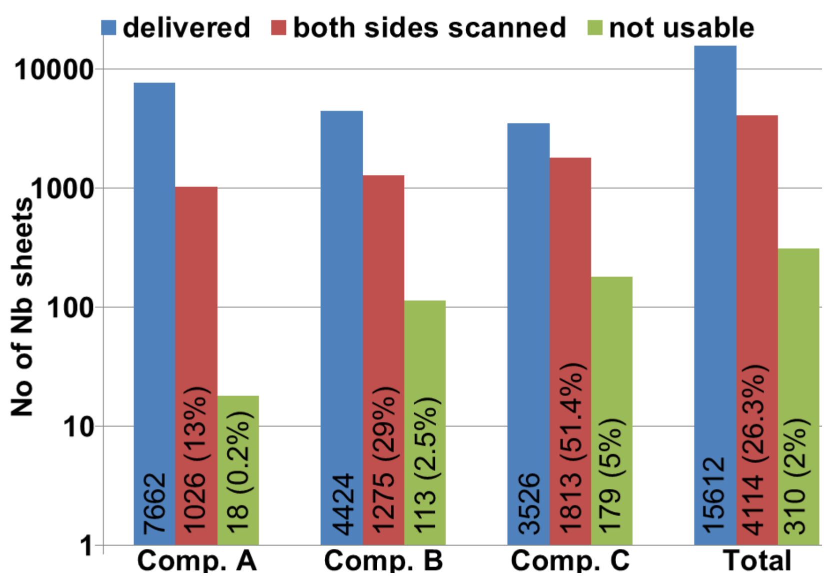
From preparatory phase to the industry

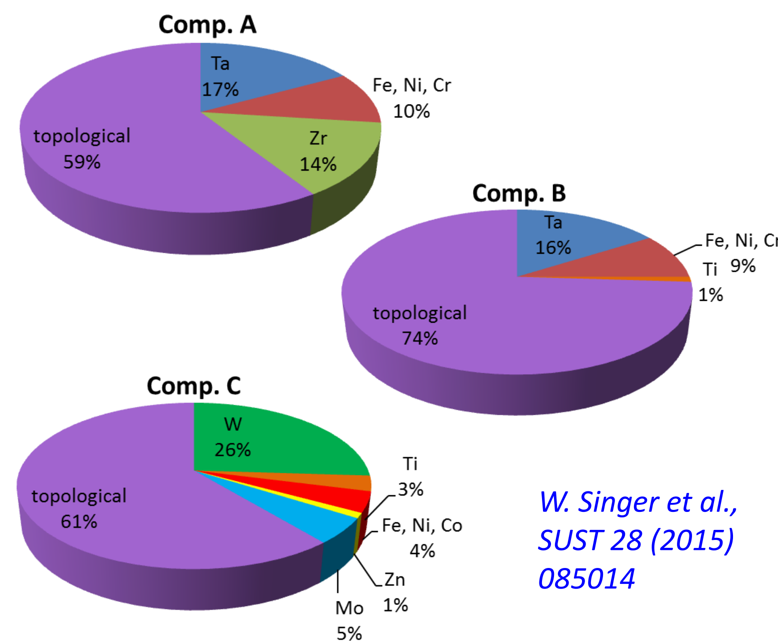
- **The R&D process** must be **complete**. The treatment recipe for E-XFEL worked out on base of ca. 100 prototype cavities.
- **Documentation must be complete**: E-XFEL specifications worked out in preparation phase
- Work out the **procurement strategy**, **delivery rate** and completion date
- **CFT** and contracts assignment
- **Set up and debugging of infrastructure using 16 "special" cavities**: the dummy (DCV) and the reference (RCV) cavities
  - **DCV** have to be used at the company for operator training, mechanical test of devices, infrastructure set up and ramp-up, final treatments test, tuning test, He tank integration, etc.
  - **RCV**: mechanically produced at industries, surface treated and tested at DESY, to be used for stepwise qualification of surface treatment infrastructure at the industries.

QC on materials and PED issue

- **ECS** on all Nb 300 sheets **(~ 15000!)**
  - Definition of the RF side
  - Labeling and marking (PED), all in EDMS
- On the 15000 sheets
  - **26% scanned on both sides**
  - **2% rejected** (foreign material > 100um, delamination, etc.)







W. Singer et al., SUST 28 (2015) 085014

Industrial production & supervision strategy

- Main principles of supervision: **cavities have to be build strictly according to the specification**. Built to print.
- **Quality Process** based on **QCP**, Quality Control Plan (also for PED)
- **Non Conformities**: if the required property of a component is not provided, a **nonconformity report** must be prepared in which the **additional procedure is proposed by the contractor**.
- **Quarantine storage area** for "rejected" or "in standby" parts.
- **All QC documents** (~ 95000), NCR (~ 1500), any document with significant production parameters (specs, protocols, PED data, etc), had been transferred and **stored in the DESY EDMS** and **analyzed in DESY cavity DB. Feedback to production process.**
- **No steadily presence at the companies**, but regularly visits.
- Regularly meetings "**Project Meeting**" on the company location (~ 2 months), **periodic progress report** (monthly)
- **Microsoft Project** Plan **based on companies** and **DESY Time Schedules** (use the plan for tracking the progress, tracking of the time schedule)

Cavity production: some numbers

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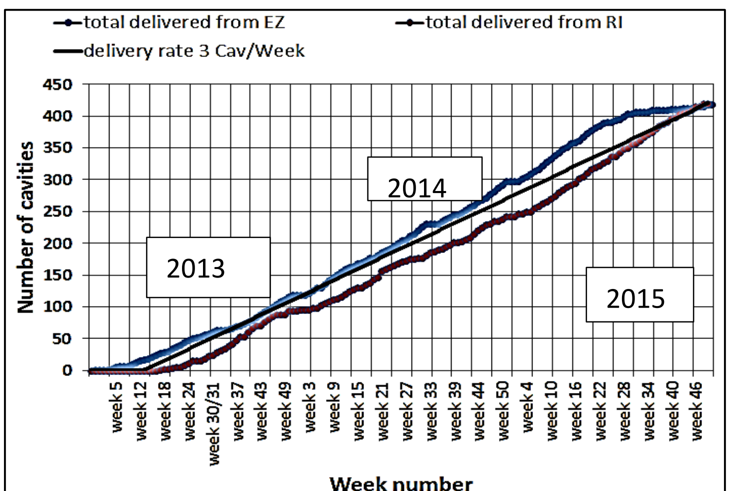
Numbers of the overall production

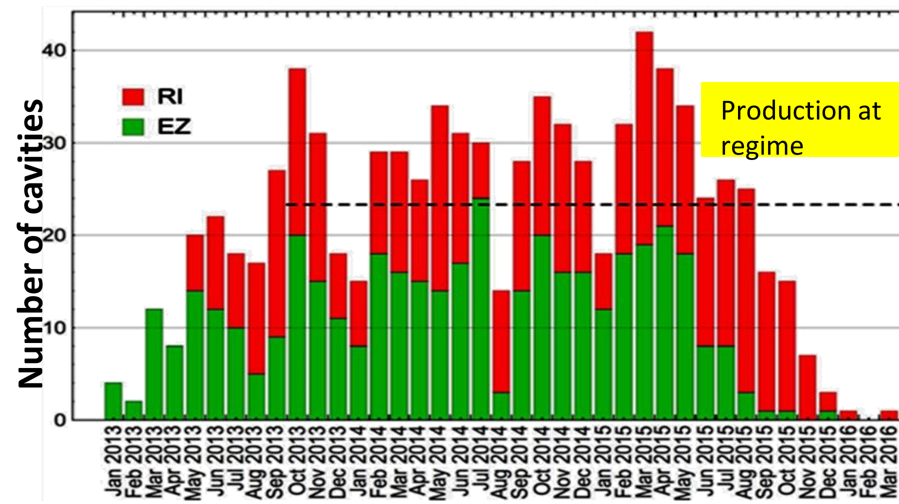
SUMMARY TABLE												
GENERAL NUMBERS				Cavities in the Analysis					Cavity not in the Analysis			
	tot for XFEL	tot produced	**tot in analysis**	Series cavities	HiGrade (tank)	HiGrade (w/o tank)	RCV (tank)	extra	RCV (w/o tank)	DCV	rej
tot	816	852	**832**	800	8	16	4	4	4	8	8
RI	408	429	**417**	400	3	9	2	3	2	4	6
EZ	408	423	**415**	400	5	7	2	1	2	4	2

Number of Cavities produced for E-XFEL (including the rejected ones then replaced):

ALL Produced 832 (100%); ALL Rejected: 8 (0.95%)

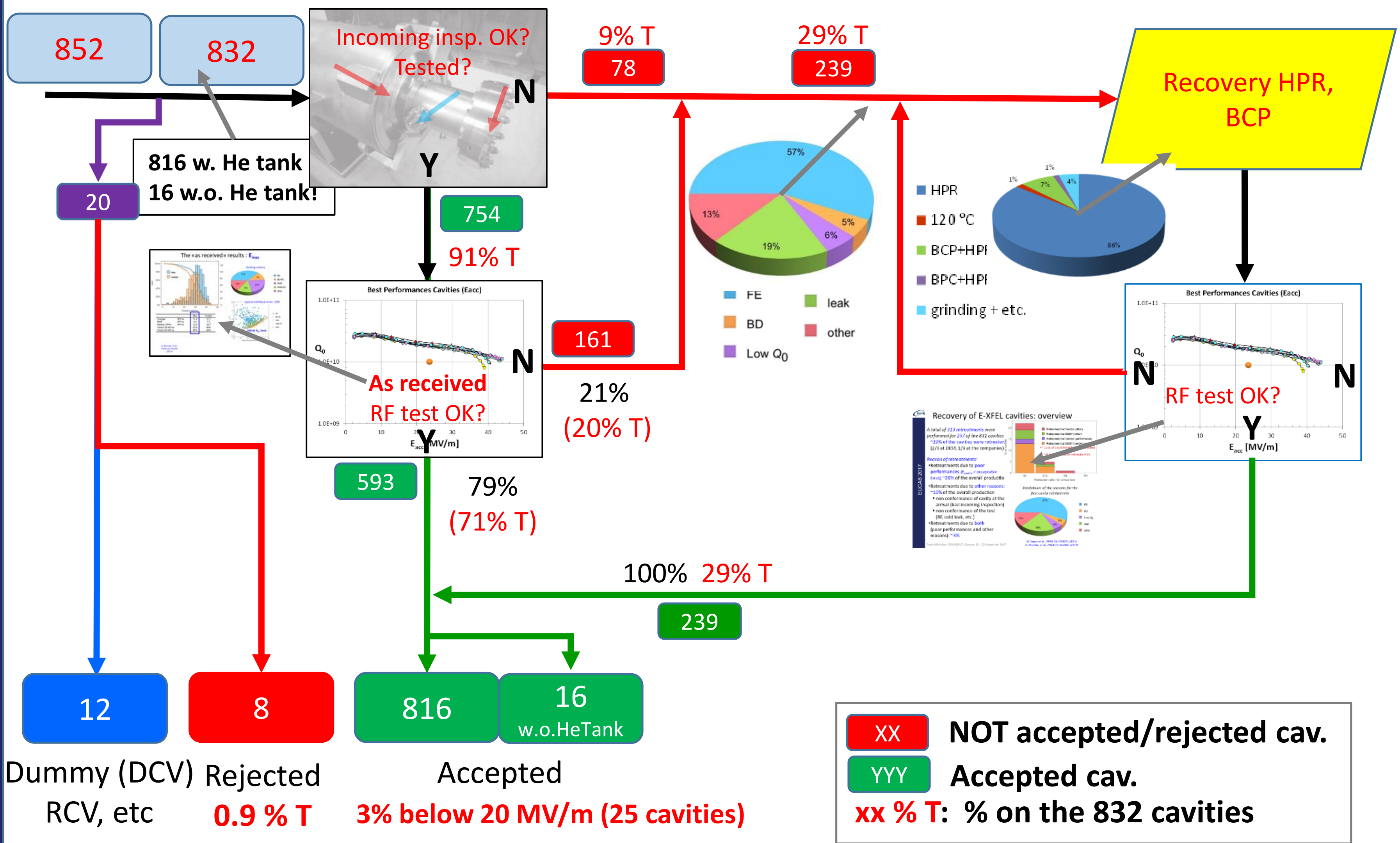
EZ: 415(100%); EZ Rejected: 2 (0.5%) RI: 417 (100%); RI Rejected: 6 (1.4%);





DESY Arrival Date

E-XFEL work flow



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Paolo Michelato, EUCAS2017, Geneva, 19 – 22 September 2017.

XFEL 1.3GHz cavities: the usable gradient

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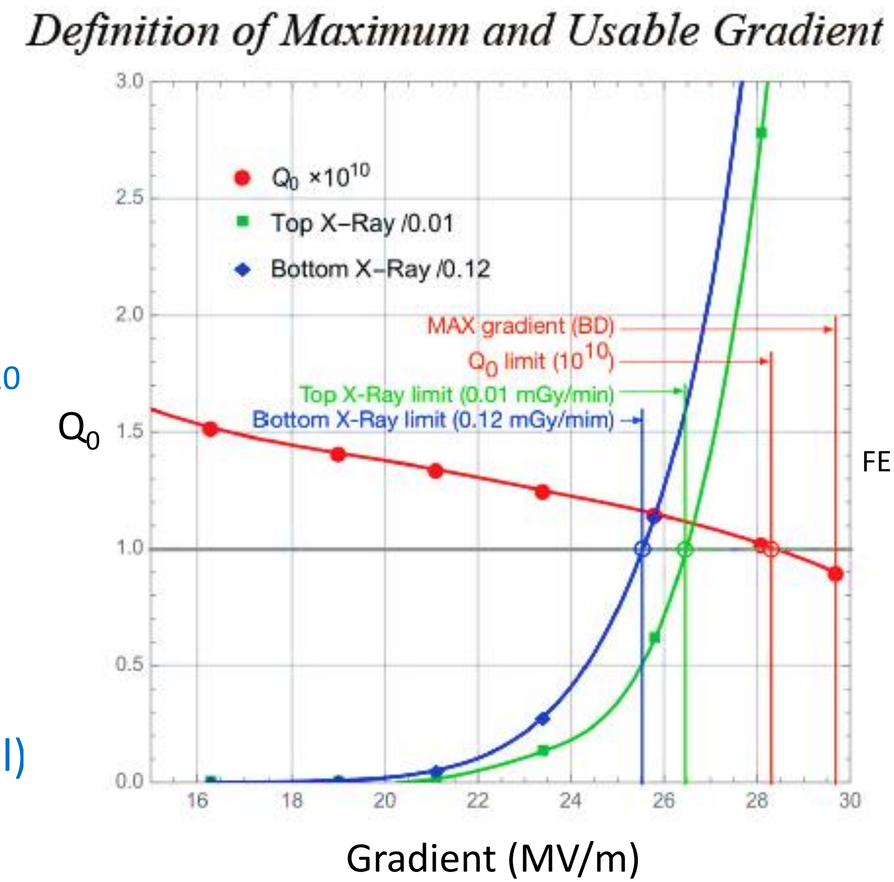
E-XFEL project goal:

- **23.6MV/m with $Q_0 \geq 1 \cdot 10^{10}$**

- Usable gradient defined **as the lowest values between:**
  - Quench gradient
  - Gradient at which Q_0 drop below 10^{10}
  - Gradient which X-ray detectors exceed thresholds (top 0.01 mGy/min; bottom 0.12 mGy/min)
- Acceptance limit for E_{usable} changed during the cavity production:

  E_{usable} ≥26 MV/m (10% more than XFEL goal)

  E_{usable} ≥20 MV/m (since May '14, 50% of production)

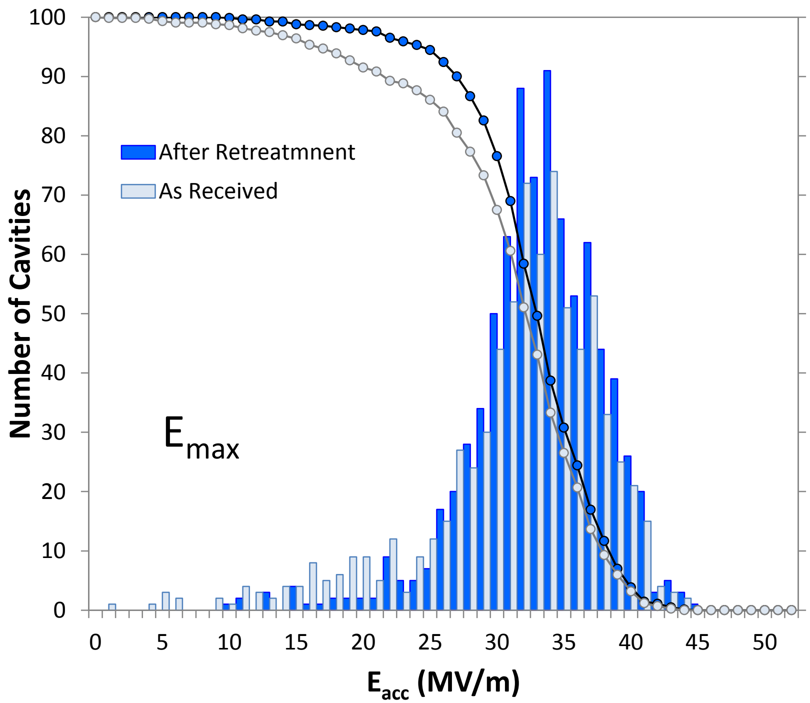


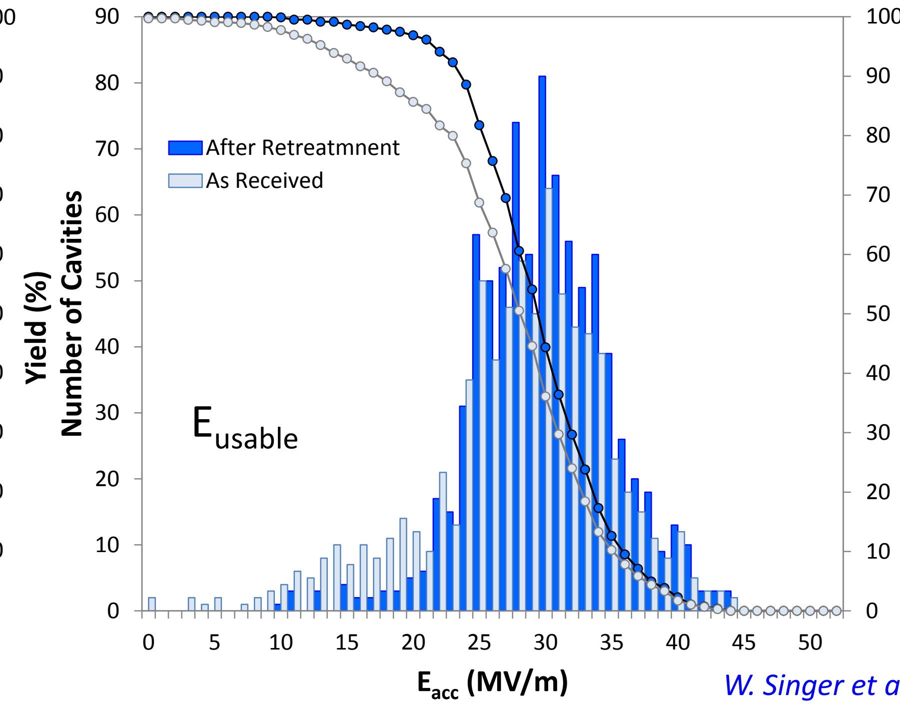
- ~ 1300 RF tests (2K, 1.48 test/cav, mean test rate: 10.4 test/w)
  - Input power limited to 200 W
  - Long pulse mode: τ_{on} 5 – 20 s, τ_{off} 50 s

N. Walker et al., MOPB086 (SRF2015)

Final Performance: the accelerating gradient

E-XFEL goal: 23.6MV/m, $Q_0 \geq 1 \cdot 10^{10}$





W. Singer et al., PRAB 19, 092001 (2016)

Final performances (after retreatments)

E max 33.0 ± 4.8 [MV/m]

(RI): E max 34.7 ± 4.4 [MV/m])

(EZ): E max 31.5 ± 4.9 [MV/m])

E usable 29.8 ± 5.1 [MV/m]

(RI): E usable 31.2 ± 5.2 [MV/m])

(EZ): E usable 28.6 ± 4.8 [MV/m])

As received

E max 31.4 ± 6.8 [MV/m]

(RI): E max 33.0 ± 6.5 [MV/m])

(EZ): E max 29.8 ± 6.6 [MV/m])

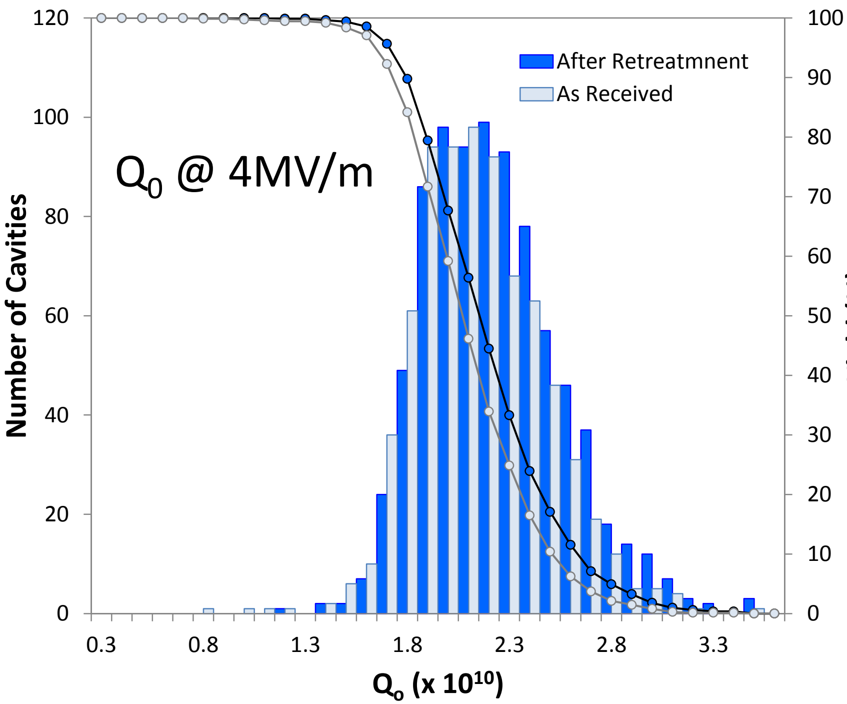
E usable 27.7 ± 7.2 [MV/m]

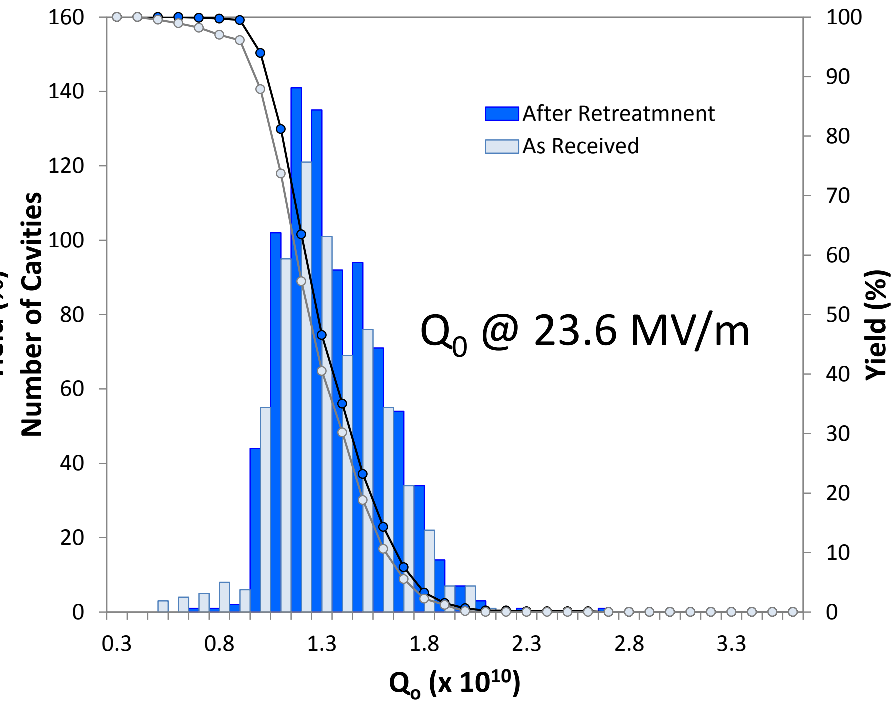
(RI): E usable 29.0 ± 7.3 [MV/m])

(EZ): E usable 26.4 ± 6.6 [MV/m])

Final performance: the unloaded Q_0

E-XFEL goal: 23.6MV/m, $Q_0 \geq 1 \cdot 10^{10}$





Final performances (after retreatments)

Q_0 @ 4 MV/m 2.23 ± 0.34 x 10^{10}

(RI): Q_0 @ 4 MV/m 2.21 ± 0.34 x 10^{10}

(EZ): Q_0 @ 4 MV/m 2.26 ± 0.33 x 10^{10}

Q_0 @ 23.6 MV/m 1.37 ± 0.25 x 10^{10}

(RI): Q_0 @ 23.6 MV/m 1.34 ± 0.22 10^{10}

(EZ): Q_0 @ 23.6 MV/m 1.41 ± 0.26 x 10^{10}

As received

Q_0 @ 4 MV/m 2.15 ± 0.32 x 10^{10}

(RI): Q_0 @ 4 MV/m 2.11 ± 0.32 x 10^{10}

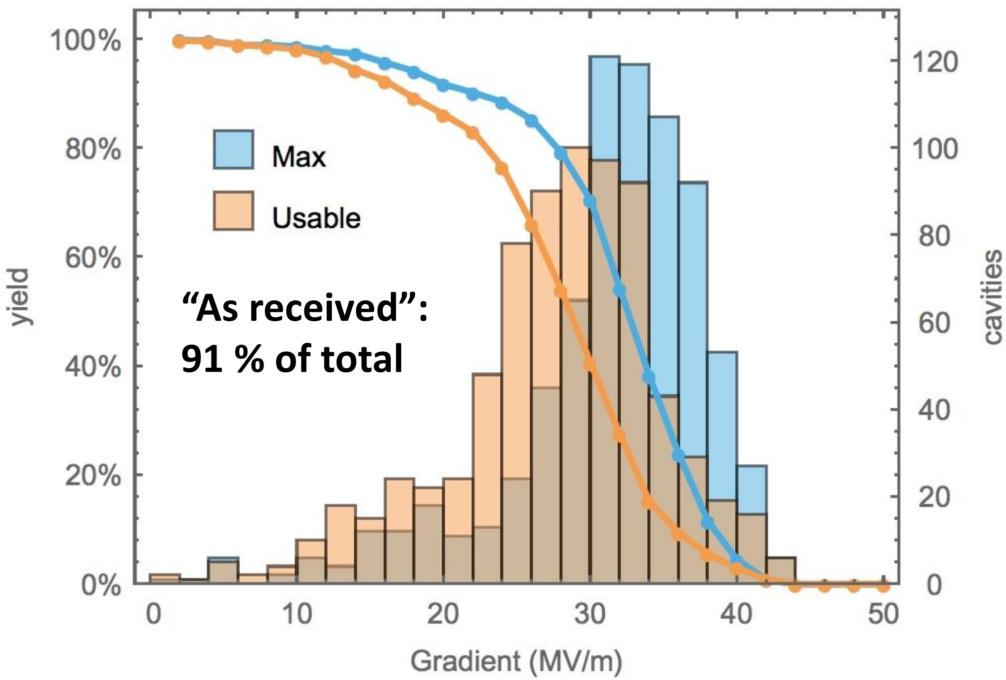
(EZ): Q_0 @ 4 MV/m 2.18 ± 0.32 x 10^{10}

Q_0 @ 23.6 MV/m 1.31 ± 0.26 x 10^{10}

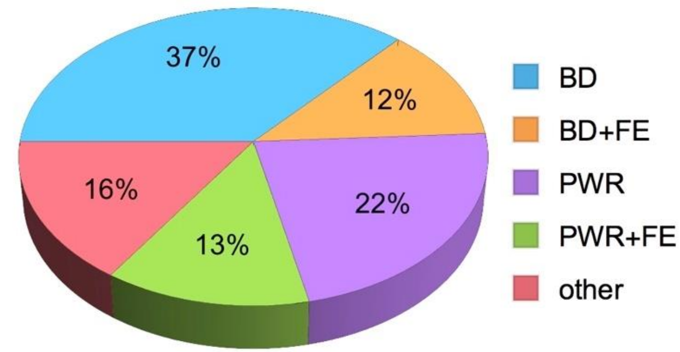
(RI): Q_0 @ 23.6 MV/m 1.29 ± 0.24 x 10^{10}

(EZ): Q_0 @ 23.6 MV/m 1.34 ± 0.28 x 10^{10}

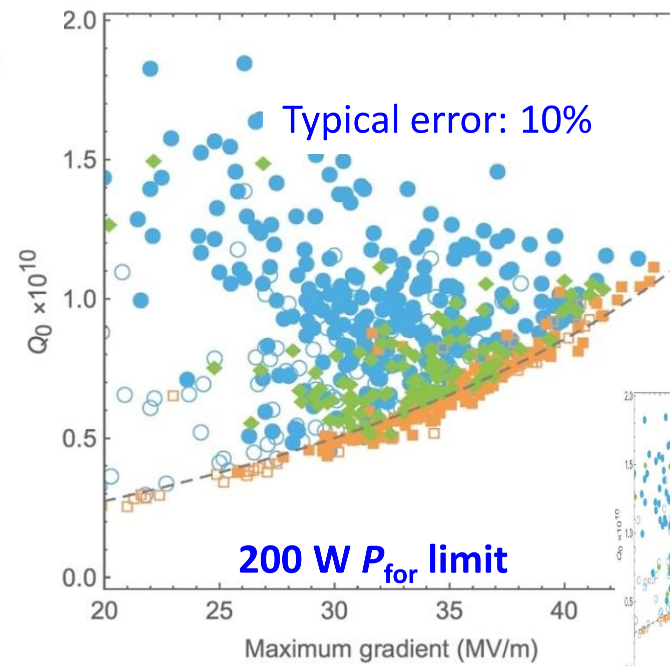
The «as received» results : E_{max}

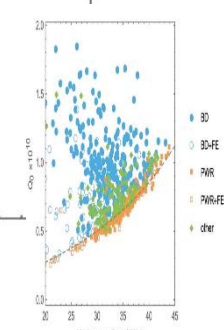


limiting criteria



		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%





D. Reschke, et al., PRAB 20, 042004 (2017)

The «as received» results : E_{usable}

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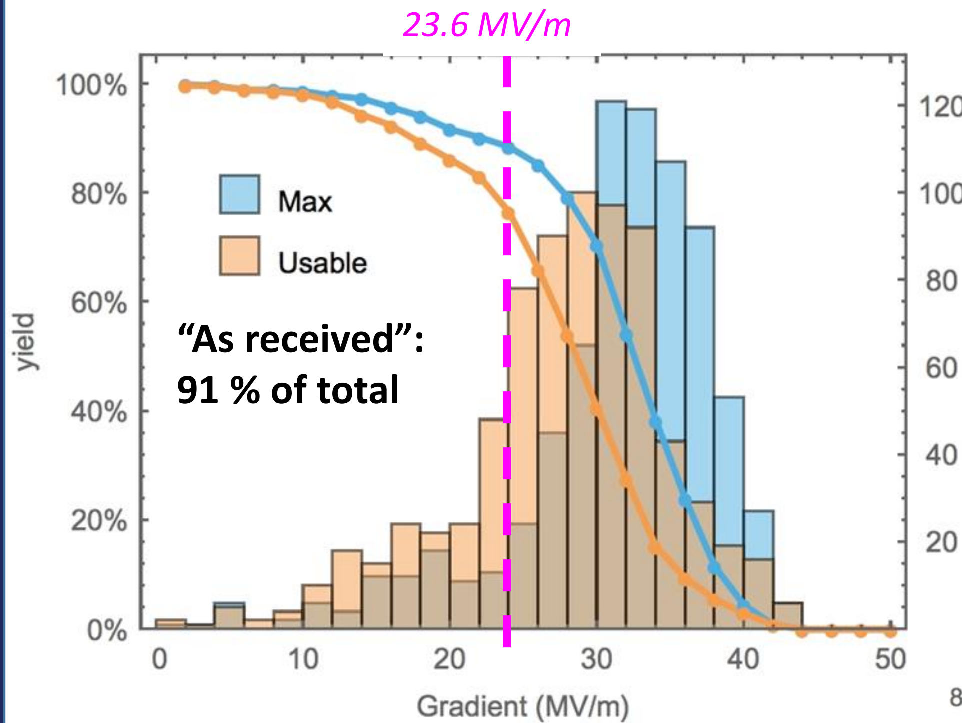

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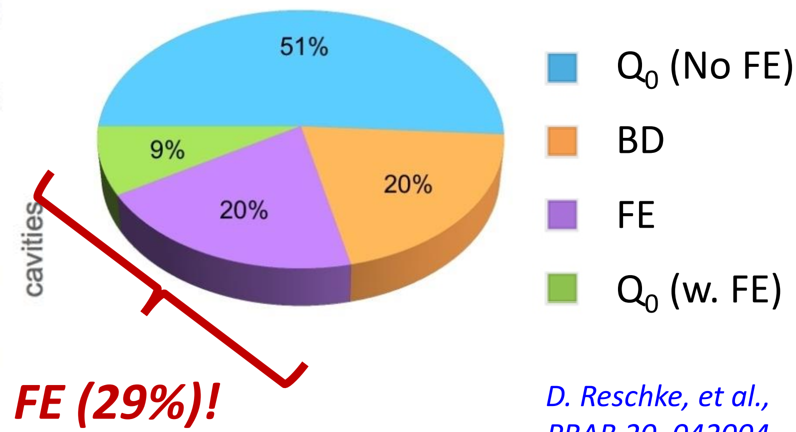

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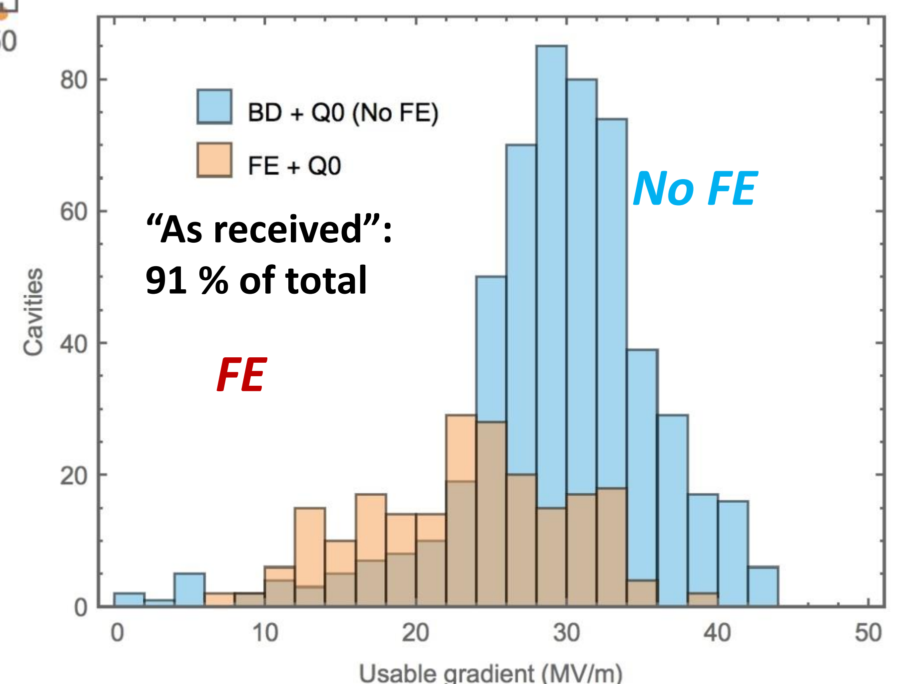


FE is the dominant limiting factor for E < 24 MV/m

Recovery of low perfomance cavities

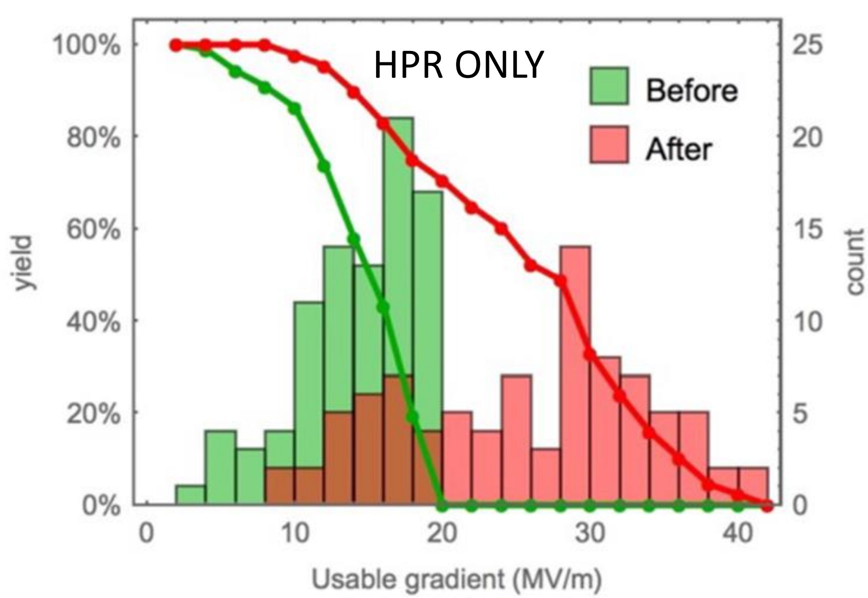
Strategy and results adopted for the **poor performance cavities**

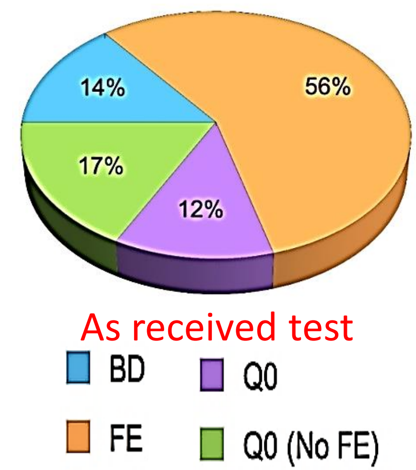
E_{usable} <20 MV/m since May '14 (before < 26MV/m)

- **Cavities retreated: ~30%**
  - ~10% **not tested**, due to incoming inspection, etc.
  - ~20% poor performances, cold test failure, etc.

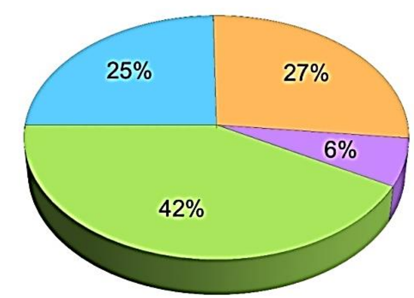
50% for E_{usable} < acceptable limit

- **Kind of retreatment**
  - **HPR (~ 86%), average improvement Eusable of about 8 MV/m**
  - **10 μm BCP** + HPR + 120 °C (~ 9%)
  - **Special recovery** (grinding + 20 μm BCP + 20 μm EP)





As received test



After retreatments

W. Singer et al., PRAB 19, 092001 (2016)

Final Performances and impact of retreatment E_{acc}

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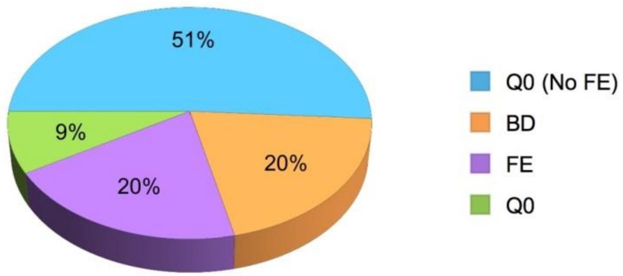
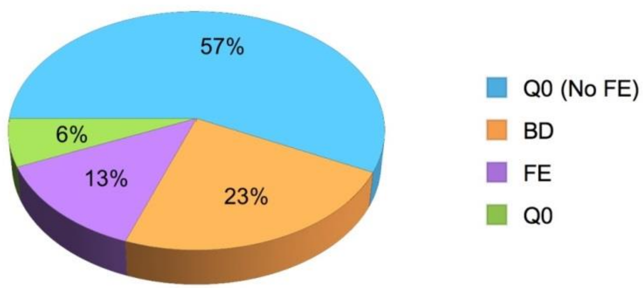
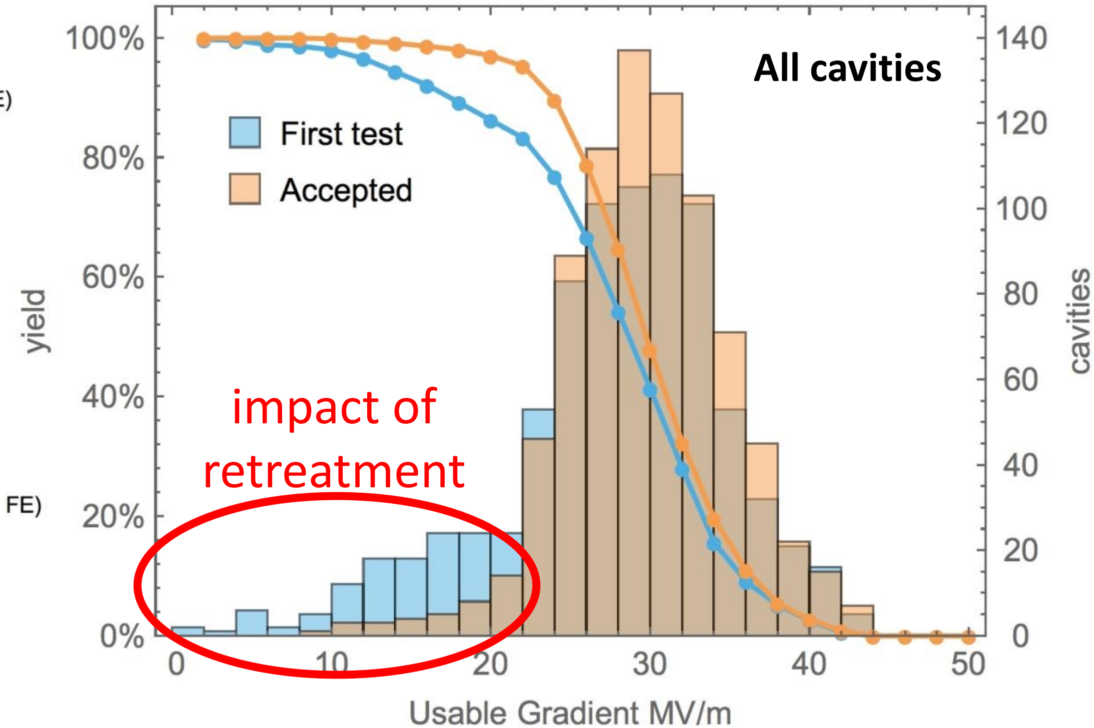
First test



Accepted test





D. Reschke, et al., PRAB 20, 042004 (2017)

		Maximum	Usable
Average gradient	MV/m	33.0	29.8
Rms	MV/m	4.8	5.1
Yield ≥ 20 MV/m		98%	97%
Yield ≥ 26 MV/m		94%	79%

Yield at 20 MV/m is not 100% since 3% of cavities were accepted with lower gradient

Two recipes comparison: Final EP & Flash BCP

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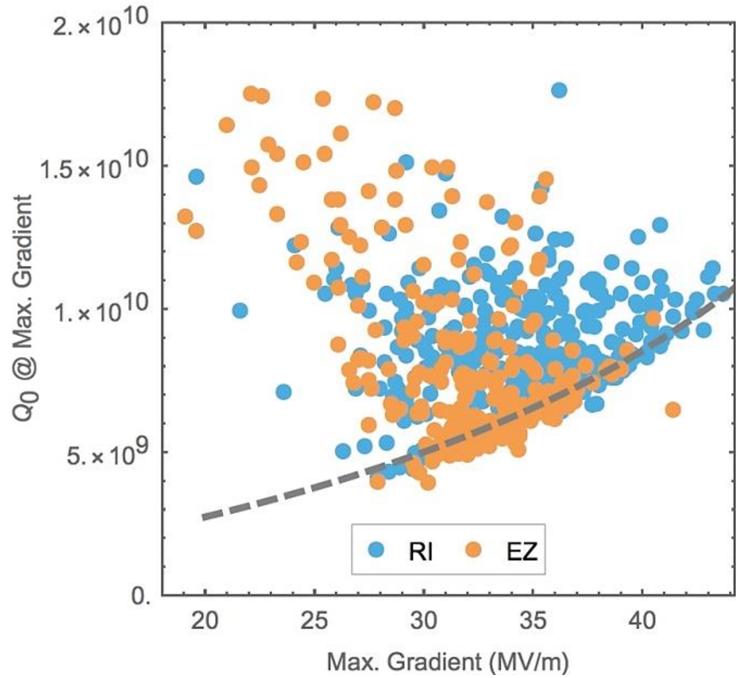
Two recipes for XFEL

The Q slope at high field is the main reason of the lower gradient (~ 4 MV/m) measured for the Flash BCP cavities w.r.t. the Final EP ones



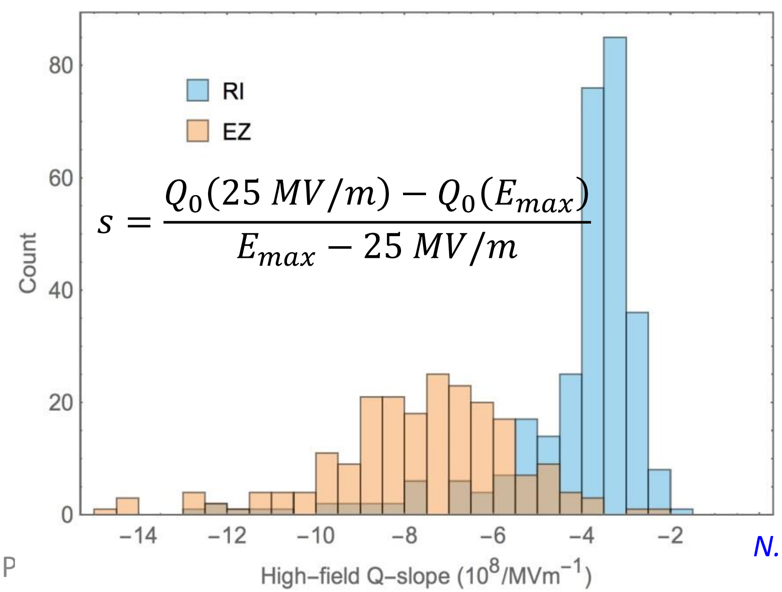
Final EP:

- **No strong dependence on Q_0; Limited usually by bd**

Flash BCP:

- **Strong Q_0 slope limit the E_{max}; at low gradient higher Q_0**

D. Reschke, et al., PRAB 20, 042004 (2017)



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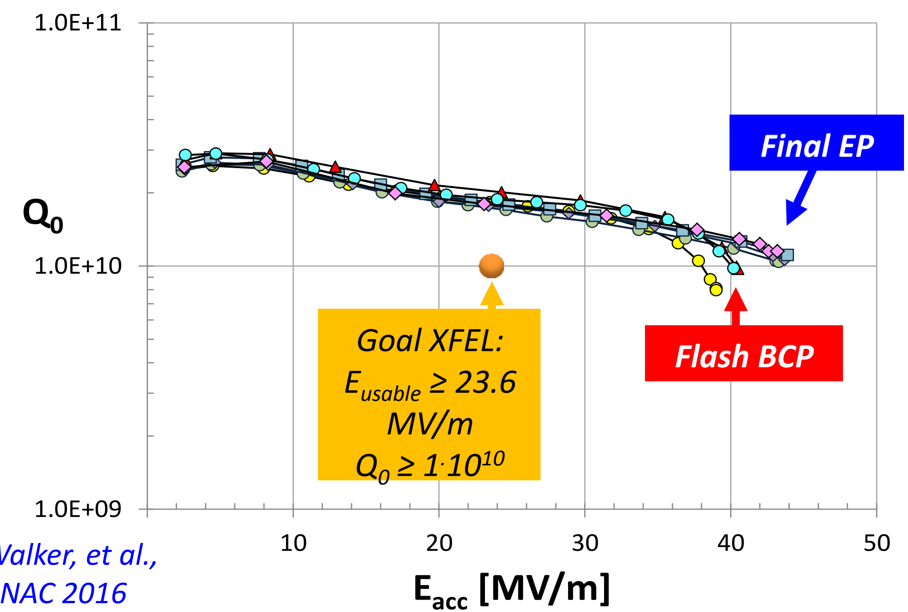
N. Walker, et al., LINAC 2016

Best Performances Cavities (Eacc)



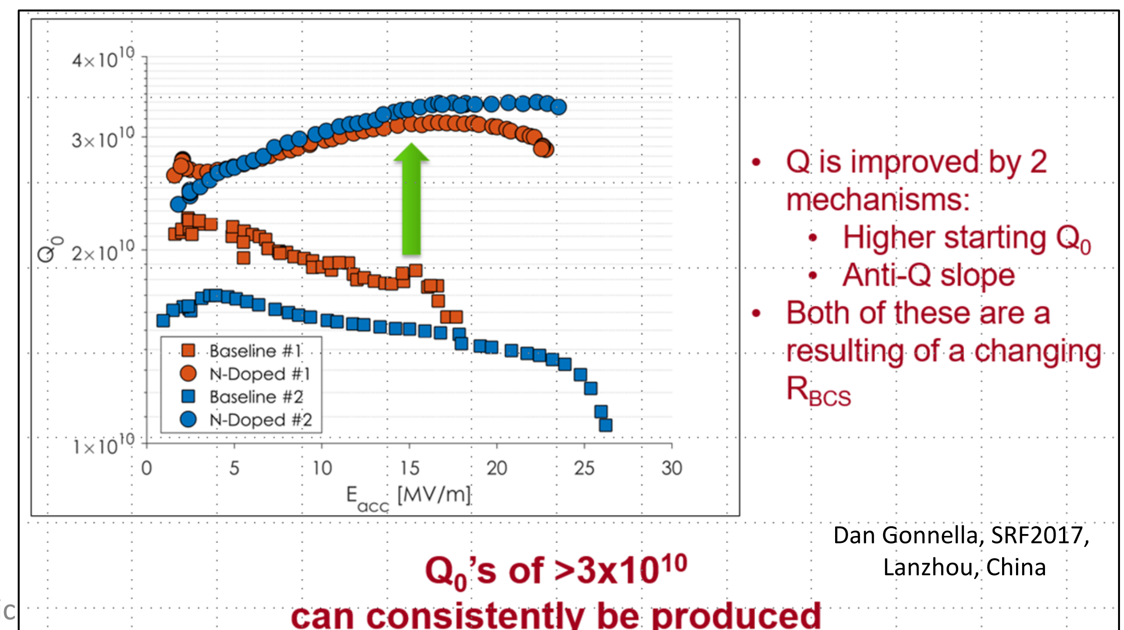
LCLS-II: introduction

- The **SRF linac** is closely based on the **XFEL/ILC/TESLA Design**
- **35 cryomodules** each with 8 cavities, **~ 330 cavities** to be produced, production under way. Rate: ~ 4 cav/week company.
- **Very ambitious acceptance criteria**
  - **$Q_0 \geq 2.5\times10^{10}$ at E_{acc} = 16 MV/m (Equivalent to Q_0 of 2.7×10^{10} in CM)**
  - **Field emission onset at $E_{acc} \geq 17.5$ MV/m**
  - **Maximum $E_{acc} \geq 19$ MV/m**
- Production recipe: based on the **Nitrogen Doping** technique
- Two companies already experienced with E-XFEL production committed: **EZ and RI**
  - Infrastructure qualified, trained personnel, etc.
- **Cavities tested "as received".**
- **QA / QC:** similar to the E-XFEL one. 3 acceptance levels. >100 documents /cavity
- **Two niobium vendors**: Tokyo Denkai (TD) and Ningxia OTIC (NX)

LCLS-II High-Q_0 recipe: the Nitrogen doping

- Recipe developed at **FNAL and JLAB**
- Recipe quite similar with the E-XFEL one
  - Major change: **N_2 exposition of the hot cavity during the heat treatment, thin layer removal by 2nd EP etching**
- **Transferred to the industry** using qualified cavities prepared at JLAB and FNAL, to qualify the **infrastructures for the doping**.
- Recipe developed with **ATI Nb**, production on **Ningxia OTIC and Tokyo Denkai material.**

F. Marhauser, IPAC2017, Copenhagen

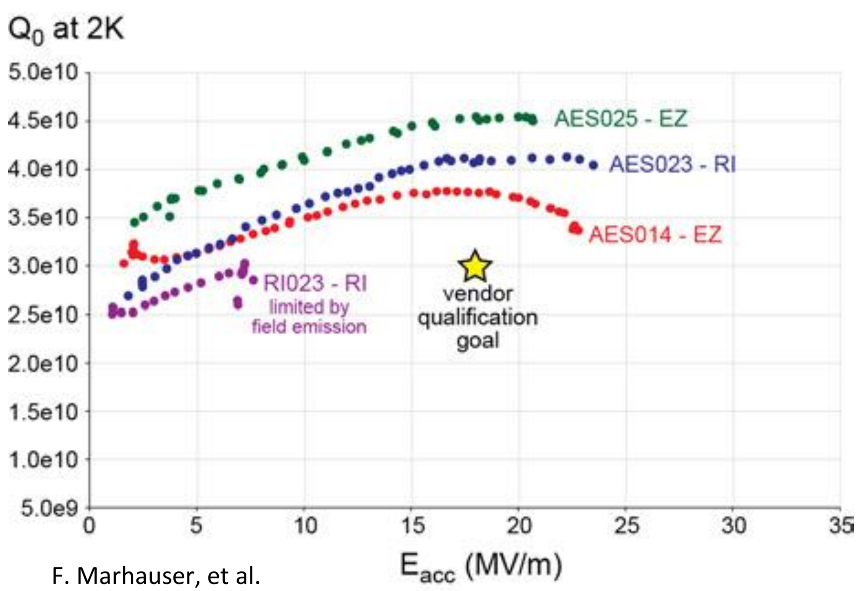


Q_0 improved by a factor ~3

Preparatory phase, first production recipe

Technology transfer of the **doping** recipe

- Infrastructure set up:
  - UHV furnace
  - N_2 lines, flow controller, pressure gauges, plc, etc.
  - EP parameters
- Process verification using reference pre-processed cavities to validate the nitrogen doping and the light EP



F. Marhauser, et al.
IPAC 2017, Copenhagen

ORIGINAL RECIPE

- Cavity mechanical fabrication
- Bulk EP: 140 μm
- Heat treatments: 800°C, 3 h
- DOPING: 800 °C, 2 min, 20 – 30 mTorr, Nitrogen
- 800 °C, in vacuum, 6 minutes Cooling to room temperature
- Tuning
- Light EP: 5 – 7 μm
- Fine tuning with fms
- Tank integration
- Standard Clean Room process

The updated production recipe

Thicker damaged layer at the surface

Updated recipes **needed to fix the effect of limited flux expulsion.**

- The bulk property of the Nb sheet, as grain size, used for cavity production significantly affects the flux expulsion efficiency during cooldown and consequently impacts on the residual resistance.
- NX material for LCLS production have small grain size and require **higher heat treatment temperature** to have better magnetic flux expulsion. 3 lots produced: A, B, C. (≥ ASTM6, in some case for lot C ≥ ASTM7).

900°C OK for Tokyo Denkai
950°C OK for NX (A + B)
975°C OK for NX (C)

These 3 recipes give $Q_0 > 2.5 \times 10^{10}$

UPDATED RECIPE

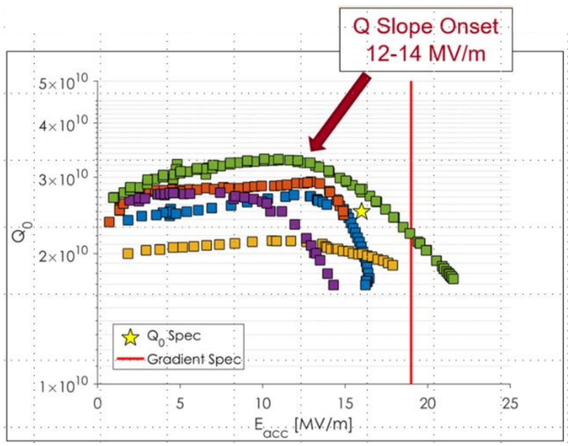
1. Cavity mechanical fabrication
2. Bulk EP: 200 μm
3. Heat treatments: 900°C, 3 h
4. DOPING: 800 °C, 2 min, 20 – 30 mTorr, Nitrogen
5. 800 °C, in vacuum, 6 minutes Cooling to room temperature
6. Tuning
7. Light EP: 5 – 7 μm
8. Fine tuning with fms
9. Tank integration
10. Standard Clean Room process

Dan Gonnella, SRF 2017,
Ari Palczewsky, SRF2017

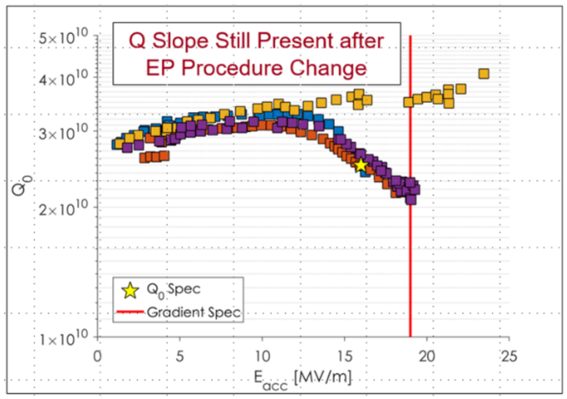
LCLS-II results: vendor A

- **First part of production**: several problems encountered that produced cavities **not acceptable.**
  - **EP parameters not optimized** (EP temperature too high)
  - **Surface roughness** before bulk EP too high
  - **Production** started mainly with **NX material** (flux expulsion problem)
  - **About 50 cavities** are under investigation, proper **fixing is under way.**
- **Production stopped, problems fixed**, some parameters changed.
- **Production resumed**.
  - ~ 40 cavities produced after restart.
  - About 20 tested with successfully results, **no evidence of Q slope, anti Q slope well visible.**

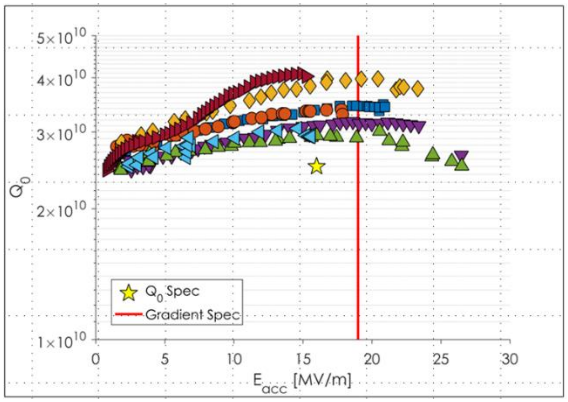
Dan Gonnella, SRF2017, Lanzhou, China



First part of production

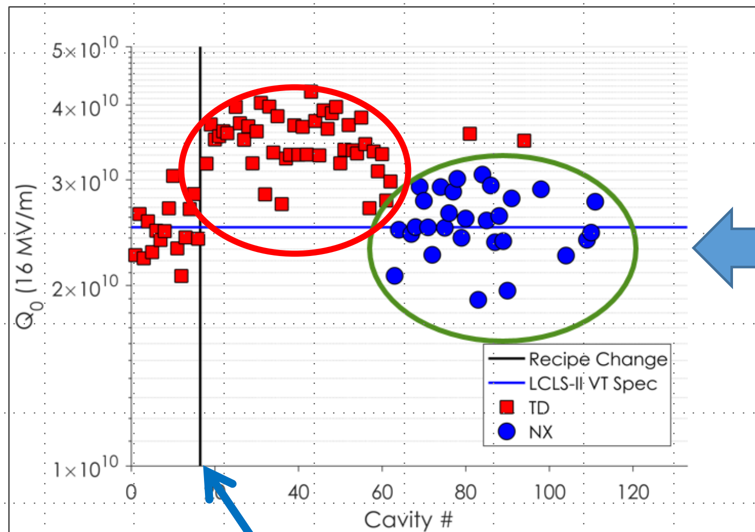


EP parameters optimized



Production successfully resumed

LCLS-II results: vendor B



Dan Gonnella, SRF2017, Lanzhou, China

18th International Conference on RF Superconductivity
Lanzhou, China July 2017

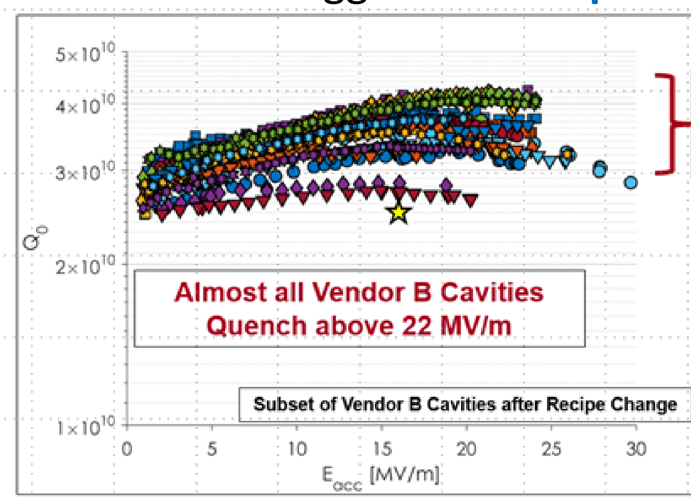
- **Vendor B** has completed fabrication of original order of **133 cavities** (July 2017)
- 99 cavities have been tested so far at JLab and Fermilab (July 2017)
- TD Cavities 900/200 preparation consistently exceed LCLS-II spec
- **NX** Cavities have middling results with **Q0's** ranging from **2 to 3x10^{10}**
- Future **NX** cavities will be treated at **950°C or at higher temperature**
  - evidence suggests this **improves Q_0**

Recipe change

New recipe: 900/200

- EP bulk: **140 µm** ⇒ **200 µm**
- Heat treatment: **800 °C** ⇒ **900 °C**

All Material 1



Majority of Cavities Now above 3x10^{10}

Magnetic field in VT Dewars no longer actively compensated – most of these tests in >5 mG

Dan Gonnella, TTC Workshop MSU.

EUCAS 2017

The low temperature nitrogen infusion

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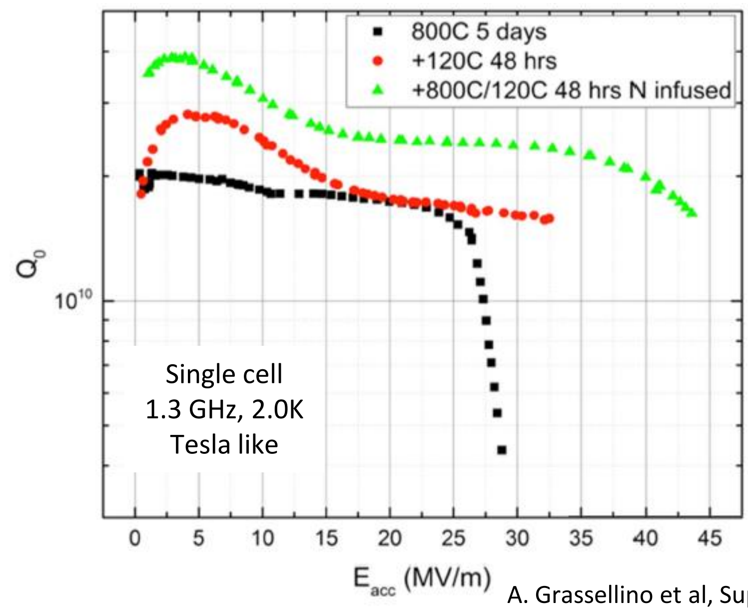
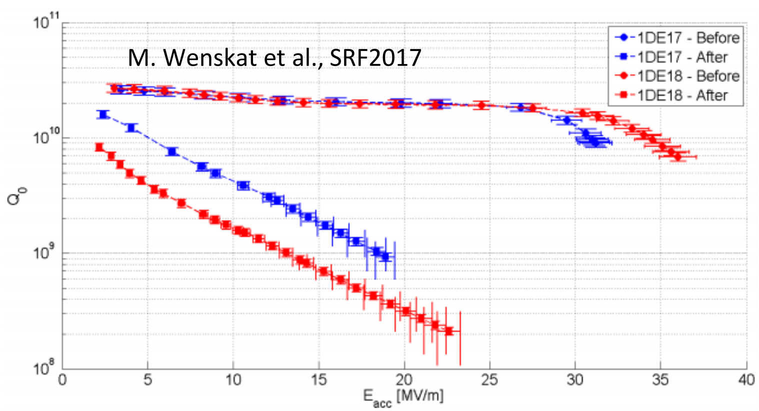
New surface treatment

- Cavity is heat treated at **800°C for 3h in UHV furnace**
- 25 mTorr of N_2 are then introduced at the end of heat treatment, **in the 120°C-200°C** temperature range, for 48h
- No further **etching needed, no light EP**
- Standard clean room process: HPR
    - The record gradient of 45 MV/m has been reached
    - BCS and surface resistance are reduced so increasing Q
    - High field Q slope is noticeably mitigated



A. Grassellino et al, Superc. Sci. Tech, 30 (2017) 094004



…but the same recipe gave bad results!

- performance degratation not due to N_2 but to a furnace contamination
- Some surface features detected by SEM and EDX on niobium samples

There is still some unclear issue on otpimal N_2 conditions. Particular care must be given to furnace conditions (vacuum level, RGA,…) in order to avoid surface contaminations

What we have learned?

- **TESLA** like cavity technology is **mature**: XFEL, LCLS-II.
- **2 companies** in EU **with qualified infrastructure** for large scale production
  - **Qualified personnel** at the companies **will be maintained in the future**?
- **QA / QC on process**, **infrastructure** and **plants** is a **key point** in the success of the industrialization process.
  - **Intermediate diagnostic tools** during production reduce risk of the defective cavities number
- **Proved recipe and design** is a must before starting industrialization
  - Cavity design should foresees repair action, as the He tank removal
- **FE** is one of limiting factor, and **HPR** usually **can cure it** (for XFEL > 80%)
- **Process choice** is depending on the cavity specification: BCP, EP, N_2 doping.
  - EP process ensure higher maximum accelerating gradients
- **N_2 doping** process is more "**delicate**" w.r.t. standard EP recipe.
  - Magnetic flux expulsion problem. Problem solved.
  - Magnetic hygiene is a must on cryomodule.
- **N_2 infusion**: Extremely promising results.
  - Accelerating gradients increase maintaining high Q values.
  - After infusion **no need of any further final etching**: cost reduction.
  - **No industrialization study**, investigations under way in many laboratories.
  - **Critical points** in the recipe to be investigated as **impurities effects** during the infusion.

The end

Spare slides

The E-XFEL Cavity structure

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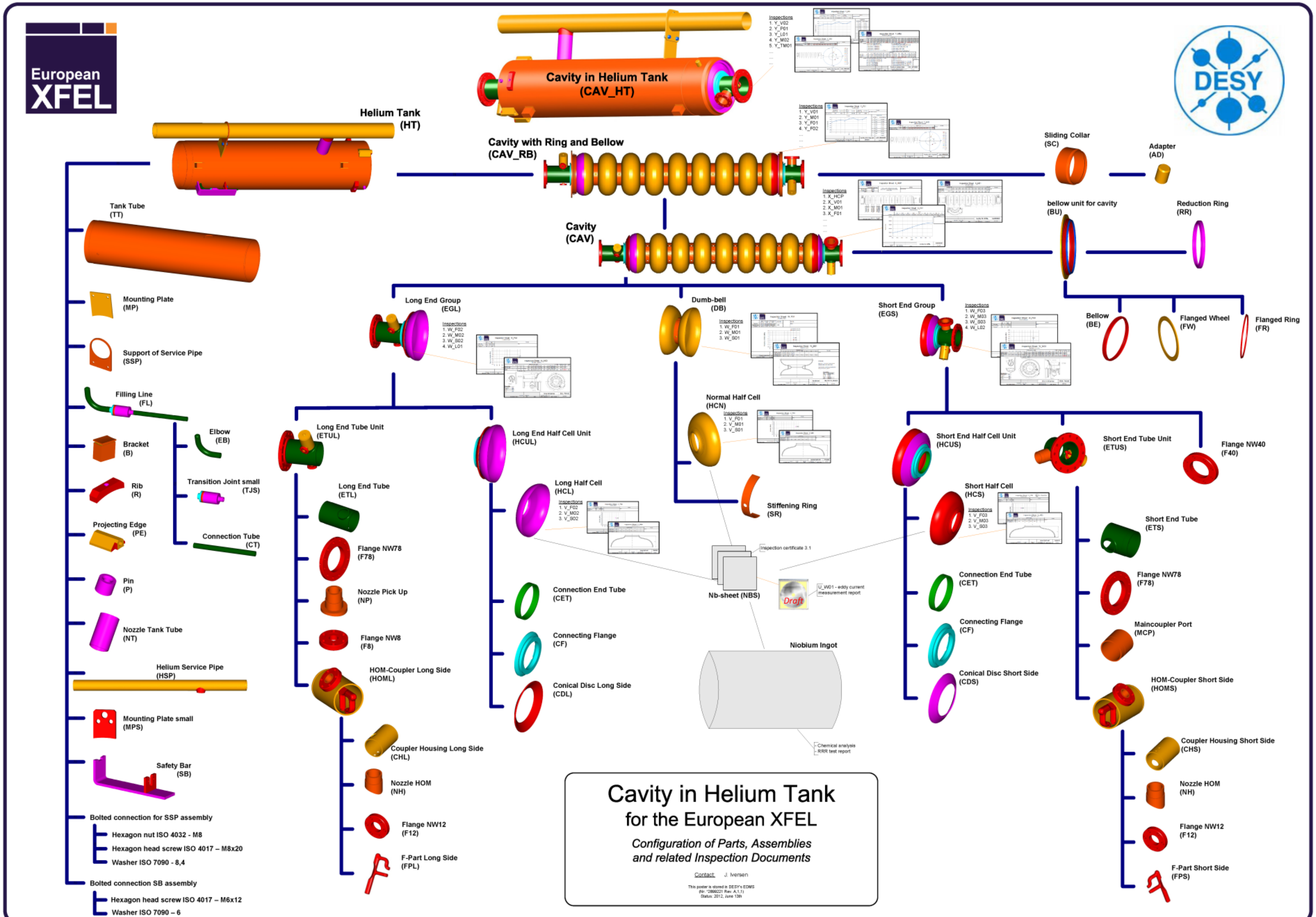

Preparatory Phase (1/3)

- Two different recipes: **Final EP and BCP Flash**, both with bulk EP
- **Review** of all parameters (mechanical, frequency, etc.)
- **Clear definition** of the production cycles
- **Definition of the external QA / QC**
  - based of the E-XFEL prescription and requirements, state of the art of cavity production, etc.
  - parameters/measurements to be collected, etc.
  - inspection templates
- **PED issues** (traceability, etc.) -> **Category IV**
  - Module B1 (review of design and drawings, material qualification (PMA))
  - Module B (company qualification, destructive/non destructive tests of test pieces, non destructive tests of PCVs)
  - Module F (non destructive tests during serial production)

Preparatory Phase (2/3)

- **Material suppliers qualification** (Nb sheets, tubes, NbTi)
  - Heraeus, Tokyo Denkai, Wha Chang: already qualified (FLASH cavities)
  - New supplier qualification based on three steps:
    - Step 1: **material testing** (RRR, Hardness, inclusion, etc.)
    - Step 2: **single-cell cavity fabrication and treatment** + RF test at cold (done at DESY)
    - Step 3: **nine-cell** mechanical cavity fabrication **at the industry**, **treatment at DESY** + RF test at cold

Company	Material testing	Single-cell RF tests	Nine-cell RF tests	Remarks
CBMM (Brazil)	failed			insufficient purity
PLANSEE (Austria)	passed	passed	passed	fabrication of the niobium sheets from ingots produced at company Heraeus
H.C. Starck (Germany)	failed			insufficient purity
Cabot (USA)	failed			unstable properties
Ningxia OTIC (China)	passed	passed	passed	all steps of niobium production available in-house
NIN (China)	passed	failed		did not deliver sheets for cavities
ITEP/GIREDMET (Russia)	passed	passed	failed	did not establish mass production

- **4 material suppliers qualified**
  - Tokyo Denkai (TD), Ningxia OTIC (N), Plansee (P) -> Nb sheets for Half Cell
  - Heraeus for all other semi-finished products (tubes, rods, etc.)

W. Singer et al., PRSTAB 19, 092001 (2016)

Preparatory Phase (3/3)

- **Cavity supplier qualification**
  - Based mainly on **mechanical cavity fabrication**
  - **2 companies qualified**:
    - Ettore Zanon (EZ) and Research Instruments (RI)

Comments

- **Both companies** had already a **large experience** in **mechanical production** of SC cavities for FLASH (tens of components) and for many other projects
- **Both companies** already have **EBW systems**
- One company (RI) has a **qualified EP system**

New infrastructure at E. Zanon and RI

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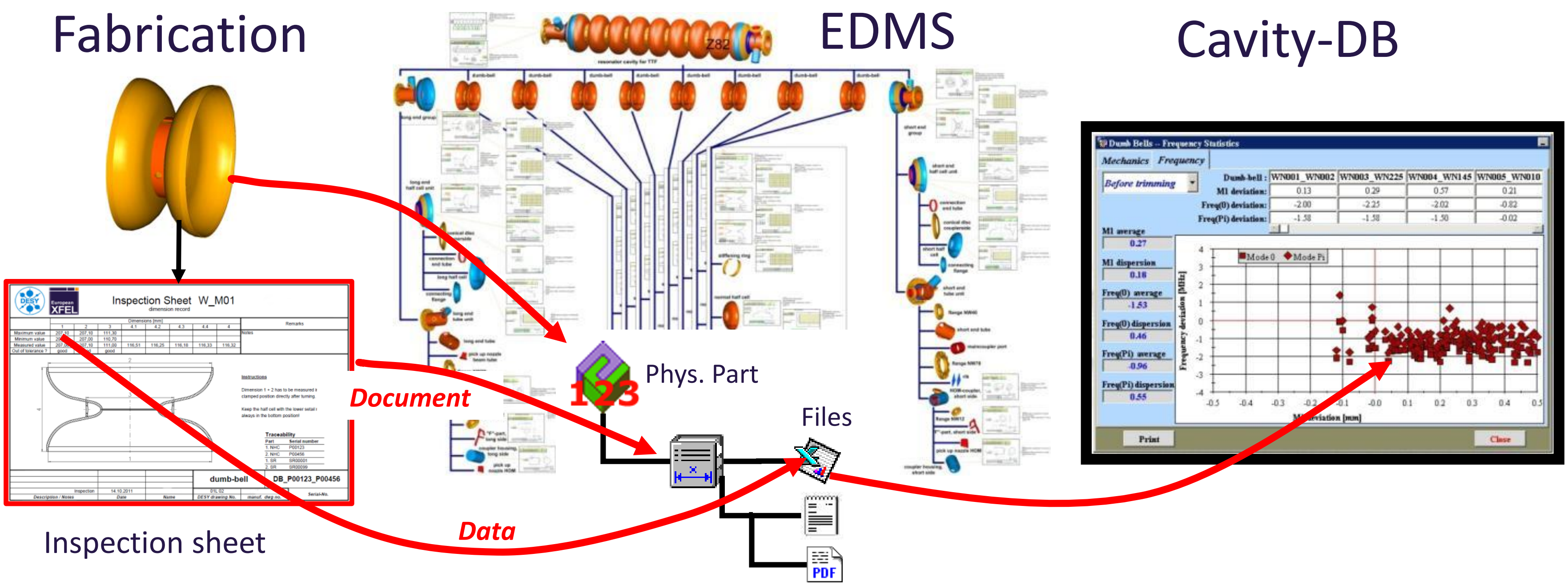
E- XFEL cavities production infrastructure comprises:

- **Electron beam welding** EBW equipment (2 per company)
- **ISO 7 & ISO 4 clean rooms** with cleaning, rinsing and BCP facility
- Ultra-pure water **(UPW) systems**, clean nitrogen and other gases
- **High pressure water rinsing equipments HPR**
- Electropolishing **EP facility**
- 800 °C annealing **furnaces**
- **Slow pumping slow venting** vacuum systems (SPSV)
- **120 °C final baking** oven (3-4 per company)
- Systems **for visual inspection** of cavity internal surface, etc.
- Tools for mech. measurement, cavity welding, integration in HT

DESY provided both companies with in-house developed

- Machine for **cavity tuning** at room temperature (**CTM**)
- **HAZEMEMA**, equipment for RF meas. of dumb bells, HC, EGs

EDMS and cavity database



Inspection sheets for QM documentation

Fabrication structure. Subassembly parts related. Procedure related.

Statistical analysis

- All XFEL SC cavity documents (specifications, inspection sheets, meeting minutes, PED data etc.) recorded in EDMS.
- EZ and RI have access to documents and data (to relevant only)

Cavity Production workflow

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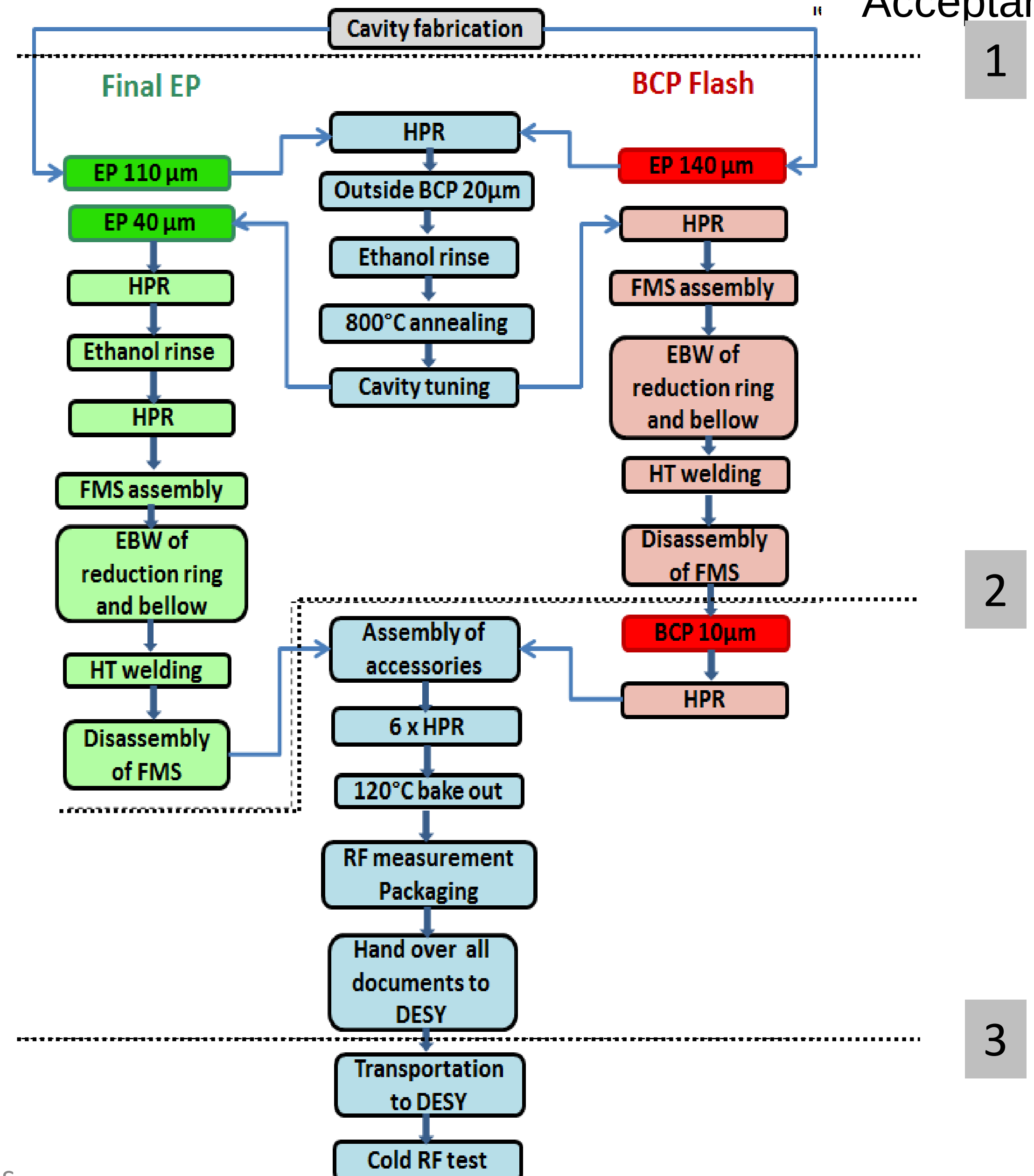
Acceptance levels



W. Singer et al., PRSTAB 19, 092001 (2016)

E-XFEL and ILC

European XFEL

Extrapolation to ILC - VT

7

- ILC TDR assumed VT acceptance > 28MV/m (XFEL >20 MV/m)
  - Average of 35 MV/m (XFEL 26 MV/m)
  - Assumed first-pass yield: 75%
  - 25% cavities retreated to give final yield of 90% >28 MV/m (35 MV/m average)
    - ➡ 10% over-production assumed in value estimate

RI results only (ILC recipe)		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 ✘ but close!
First+Second+third pass	Yield >28 MV/m Average >28 MV/m	- -		91% 33.4 MV/m

RI, EP processed cavities

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 ➡ $$$

Magnetic flux expulsion problem

- The downside of the nitrogen doping is that the cavities are more susceptible to trapping magnetic flux during cooldown, thus necessitating a much more strict ambient magnetic field requirement in both the vertical testing dewar and in the cryomodule.
- Magnetic field sensitivity force carefully magnetic hygiene on all stainless steel parts as bolts, etc. Double magnetic shield is used in vertical test.
- The Nb bulk property of the sheet material used for cavity production significantly affects the flux expulsion efficiency during cooldown and consequently impacts the residual resistance.
- Original recipe results in the first part of production at the industry, using NX and TD Nb sheets, shown poorer flux expulsion when compared with prototype material from ATI Wah-Chang.
- Grain size in Nb sheets has strong influence in cavities performances. If too small, flux trapping will produce high R_{BCS} values. Usual specification: grain size ≥ ASTM 6, but no limit for the lower limit.
- Increasing the furnace degas temperature from 800 °C to 900°C (950 °C and higher for small grain material)has been shown to improve flux expulsion.
- Moreover material have shown a thicker damage layer on the surface that could lead to a slight increase in residual resistance. Bulk removal increased from 140 to 200 µm.

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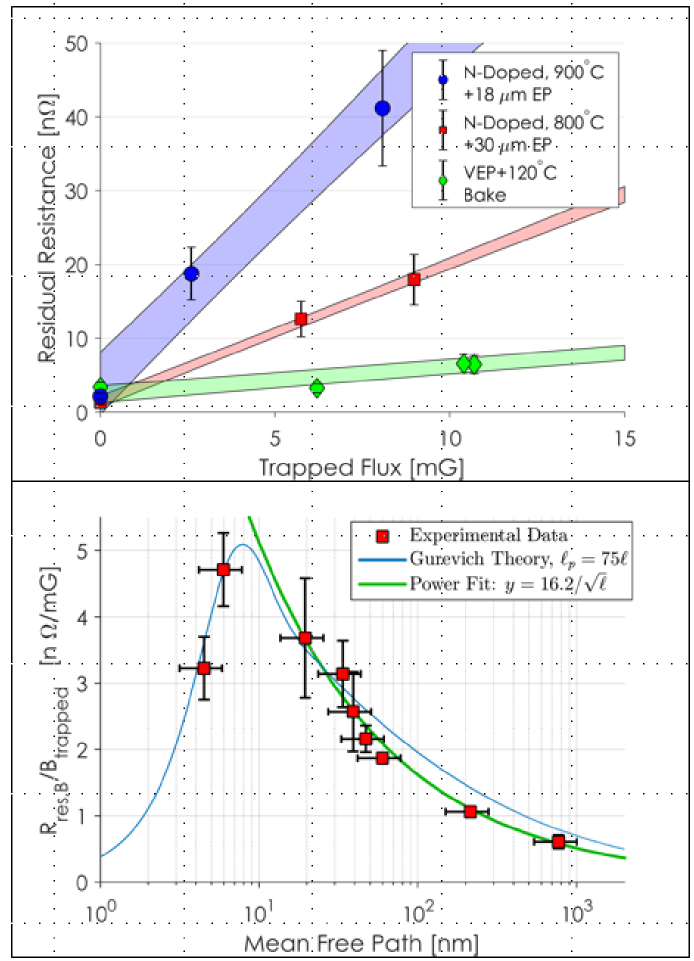
Drawbacks of N-Doping

- Q_0 is significantly improved by the lowering of R_{BCS}
- There is a tradeoff however with R_{res}
- Nitrogen-doped cavities are more sensitive to losses from trapped magnetic flux
- For the same amount of trapped flux, a N-doped cavity will have a higher R_{res} than an un-doped cavity
  - 3.4x for the LCLS-II cavity recipe
- This requires efficient flux expulsion or small ambient magnetic fields to maintain high Q_0



Presented at SRF 2015 and J. Appl. Phys. 119:073904

18th International Conference on RF Superconductivity
Lanzhou, China July 2017

Dan Gonnella, SRF2017, Lanzhou, China