深圳综合粒子设施研究院
Institute of Advanced Science Facilities, Shenzhen

Cycle of Seminars by Carlo Pagani

Seminar # 5

European XFEL: from prototypes to large scale production

Shenzhen, 30 September 2022 / INFN LASA, 30 October 2024

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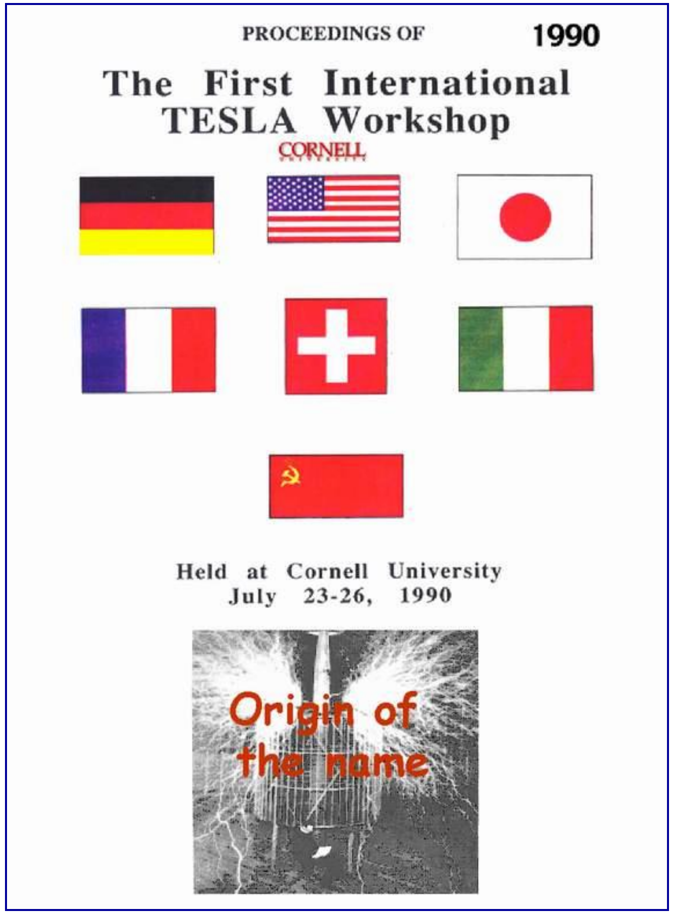
3. Preparing series production: the cavity example
4. Series production better than prototypes

Eu-XFEL by-product of TESLA

The European XFEL has been the by-product of TESLA, the Superconducting Linear Collider developped since 1990 by a large International Collaboration



The goals of the TESA Mission

Basic goals on SRF Technology

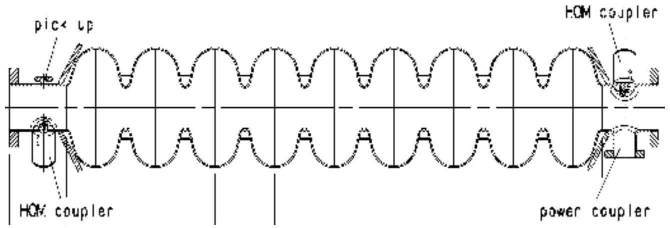
- Increase gradient by a factor of 5: from 5 to 25 MV/m
  - Push cavity performances close to the physical limit, understanding practical limits
  - Set all the required quality control for reproducibility and industrial production
- Make possible pulsed operation: Lorentz force detuning
  - Combine SRF and mechanical engineering in cavity design
  - Develop efficient Modulators and Klystrons
  - Develop new ancillaries: slow and fast tuners, couplers
- Reduce cost per MV by a factor 20: to make the LC feasible
  - New cryomodule concept for cryolosses, cost and filling factor (for real estate gradient)
  - All subsystems designed for large scale production
  - Reliability and quality control as a general guideline

Basic goals on Machine Design

- Design a Linear Collider based on the Cold Linac peculiarities
- Maximize Luminosity and optimize cost for a given plug power
- Design and quote major subsystems: DR, Positron Source, BDS, etc.
- Put all together in a consistent TDR, including cost estimation

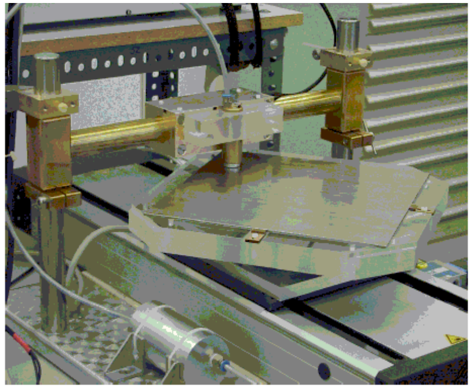
Major contributions from: CERN, Cornell, DESY, CEA-Saclay, INFN-LASA

9-cell, 1.3 GHz



TESLA cavity parameters

R/Q	1036	W
E_{peak}/E_{acc}	2.0	
B_{peak}/E_{acc}	4.26	mT/(MV/m)
$\Delta f/\Delta l$	315	kHz/mm
$K_{Lorentz}$	$\approx$ -1	$Hz/(MV/m)^2$



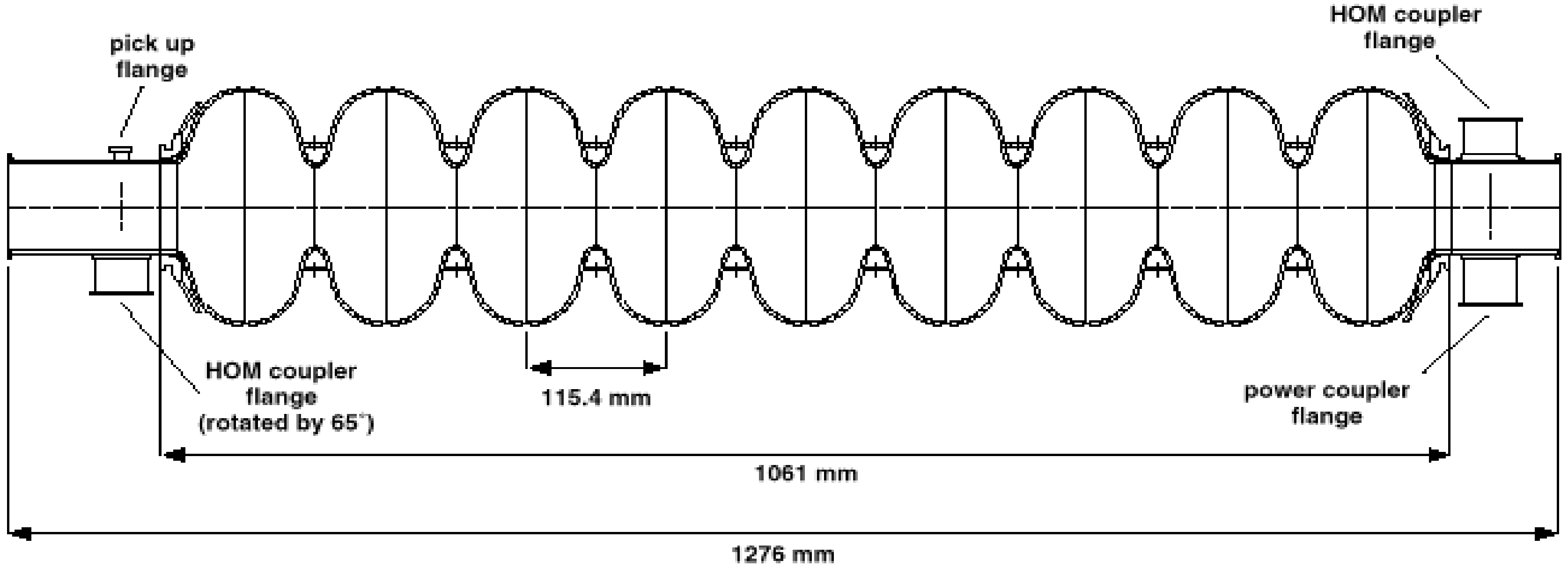
Eddy-current scanning system for niobium sheets

Cleanroom handling of niobium cavities

Preparation Sequence

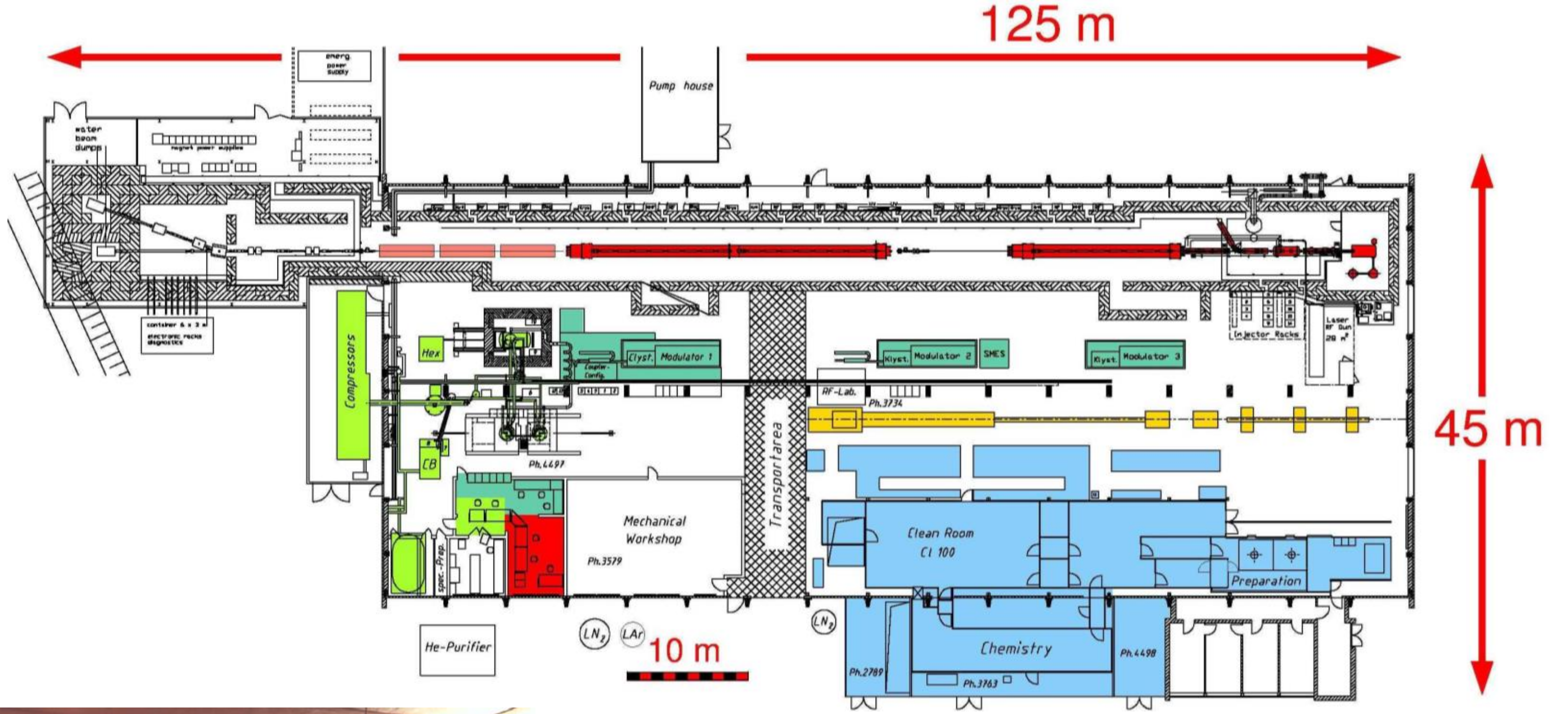
- Niobium sheets (RRR=300) are scanned by eddy-currents to detect avoid foreign material inclusions like tantalum and iron
- Industrial production of full nine-cell cavities:
  - Deep-drawing of subunits (half-cells, etc.) from niobium sheets
  - Chemical preparation for welding, cleanroom preparation
  - Electron-beam welding according to detailed specification
- 800 °C high temperature heat treatment to stress anneal the Nb and to remove hydrogen from the Nb
- 1400 °C high temperature heat treatment with titanium getter layer to increase the thermal conductivity (RRR=500)
- Cleanroom handling:
  - Chemical etching to remove damage layer and titanium getter layer
  - High pressure water rinsing as final treatment to avoid particle contamination

TESLA cavity design and rules

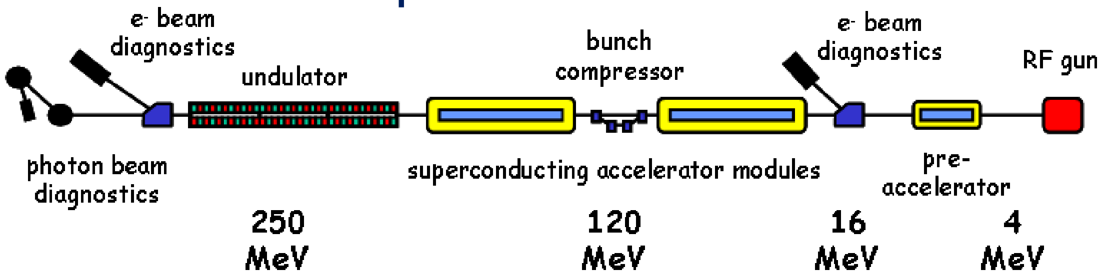


type of accelerating structure	standing wave
accelerating mode	TM0 π mode
fundamental frequency	1300 MHz
design gradient E_{acc} (TTF)	15 MV/m
design gradient E_{acc} (TESLA)	25 MV/m
unloaded quality factor Q_0 (TTF)	$> 3 \times 10^9$
unloaded quality factor Q_0 (TESLA)	$> 5 \times 10^9$
shunt impedance R / Q	1036 Ω
E_{peak} / E_{acc}	2.0
B_{peak} / E_{acc}	4.26 mT / (MV/m)
cavity bandwidth at $Q_0 = 3 \times 10^6$	430 Hz

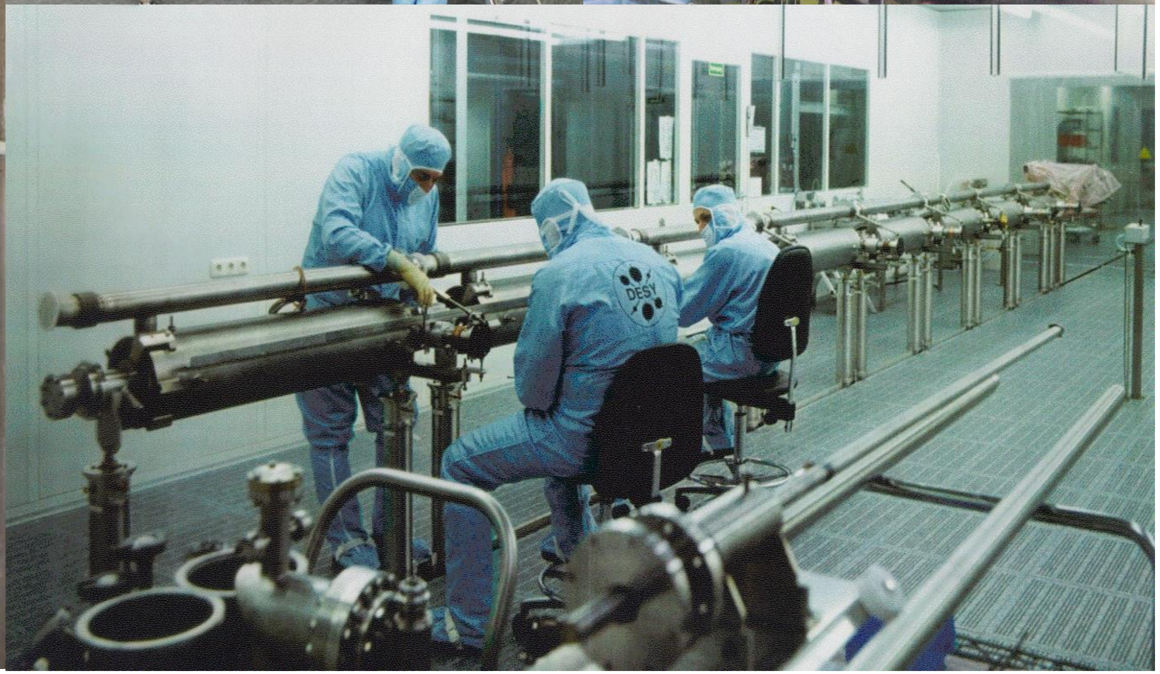
TTF: a new infrastructure at DESY



TTF as operated for SASE FEL



Preparation of TESLA Cavities



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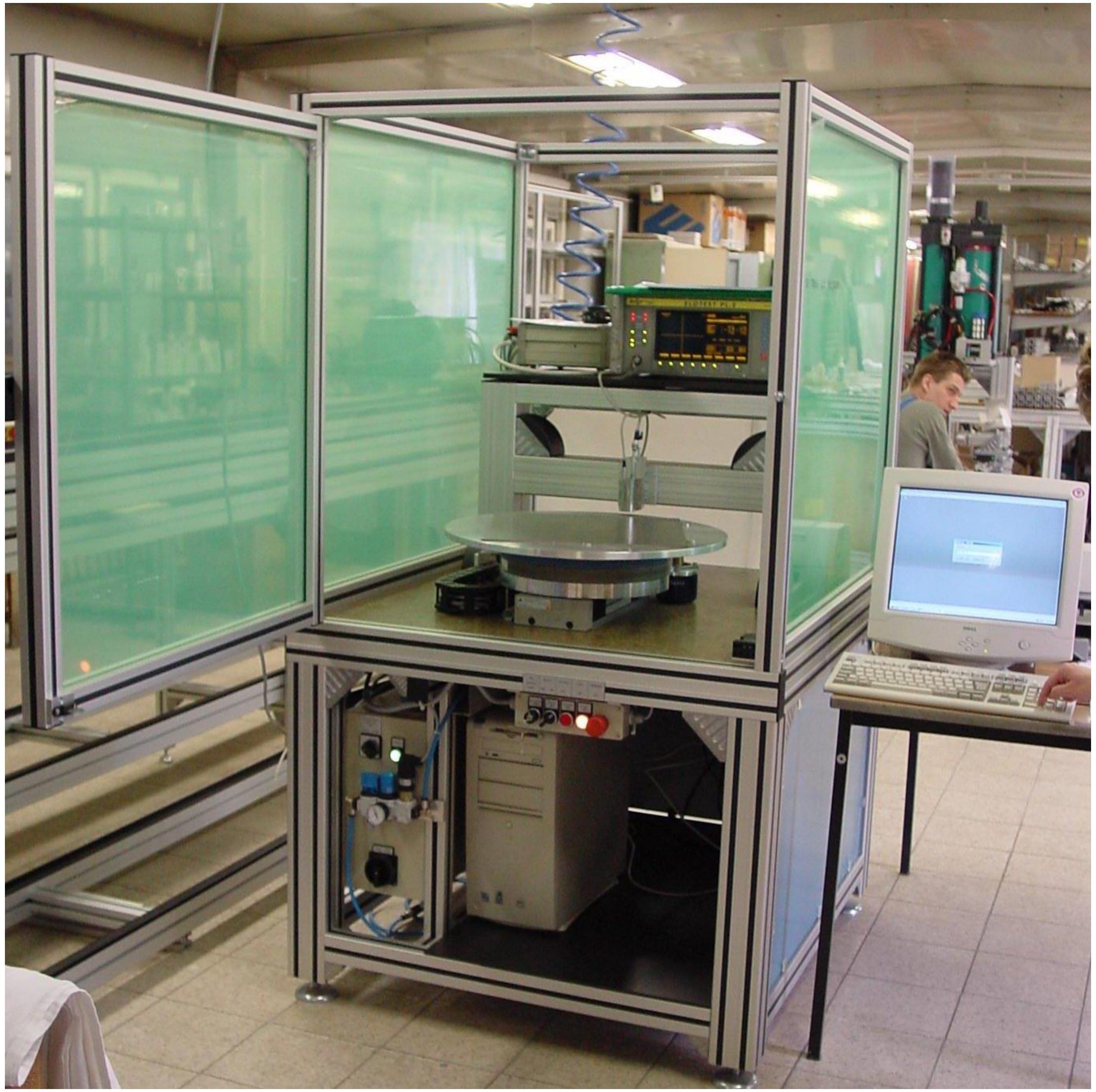
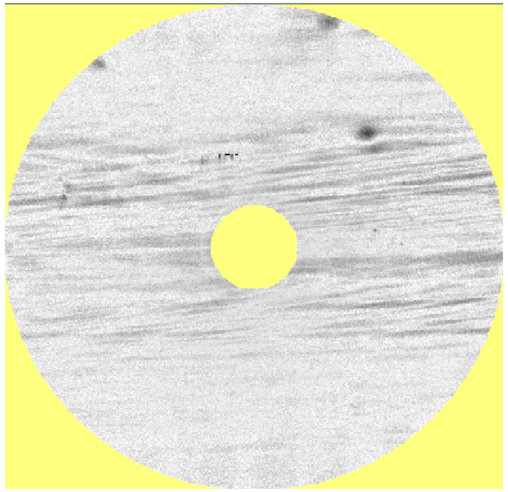
The way to improve SRF Performances

- In parallel with the machine design, **all major TESLA sub-components have been conceived, designed and protopyped for TTF**.
- Most of the process has been performed in **strict collabotration with industry**.
- Concerning SRF cavities, all the technology already mastered by industry have been further improved with the help of Labs experience. **All the mechanical fabrication done in industry**.
- The acquisition of an EB Welding machine at DESY had the strong opposition by the Director Biorn Wiik
- The matured experience on the **Niobium welding** has been transferred directly **from Labs to industry**
- Clean room operation and special surface treatments were developped at the DESY infrastructure and promptly tranferred to Industry

Eddy Current Scanner for Nb Sheets



Scanning results



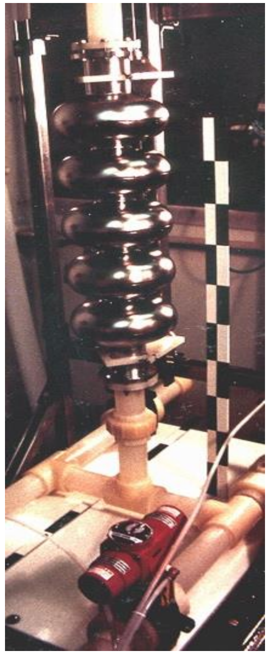
- Rolling marks and defects are visible on a niobium disk to be used to print a cavity half-cell.
- Surface analysis is then required to identify the inclusions

Learning curve with BCP

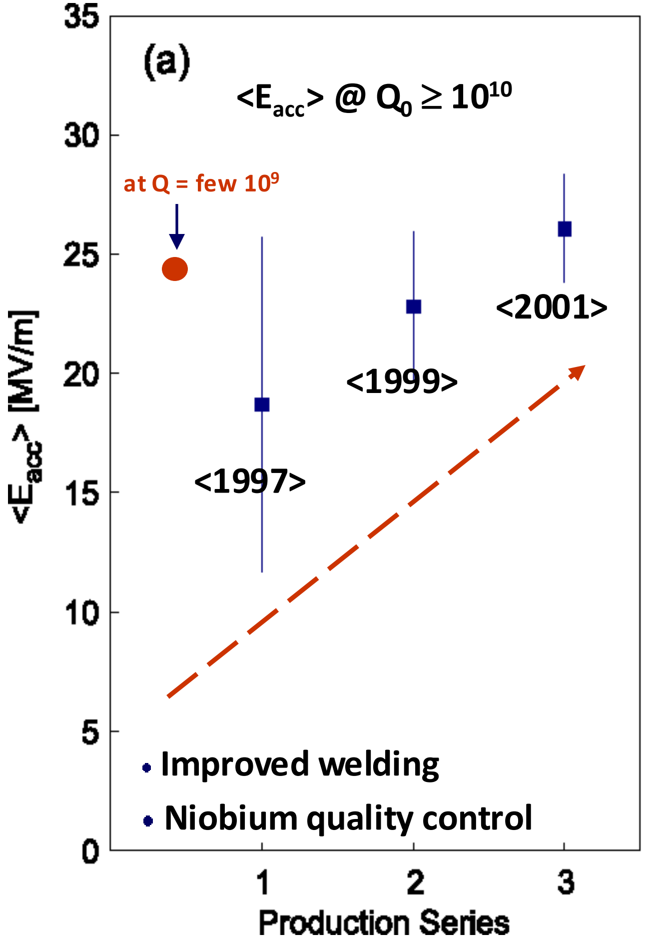
BCP = Buffered Chemical Polishing

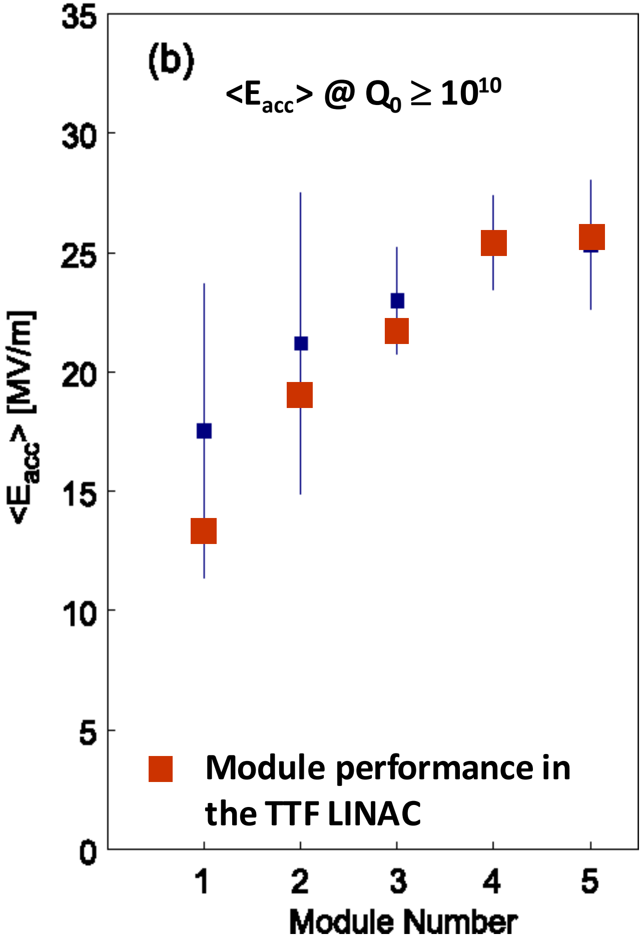
3 cavity productions from 4 European industries: Accel, Cerca, Dornier, Zanon

Cornell
1995

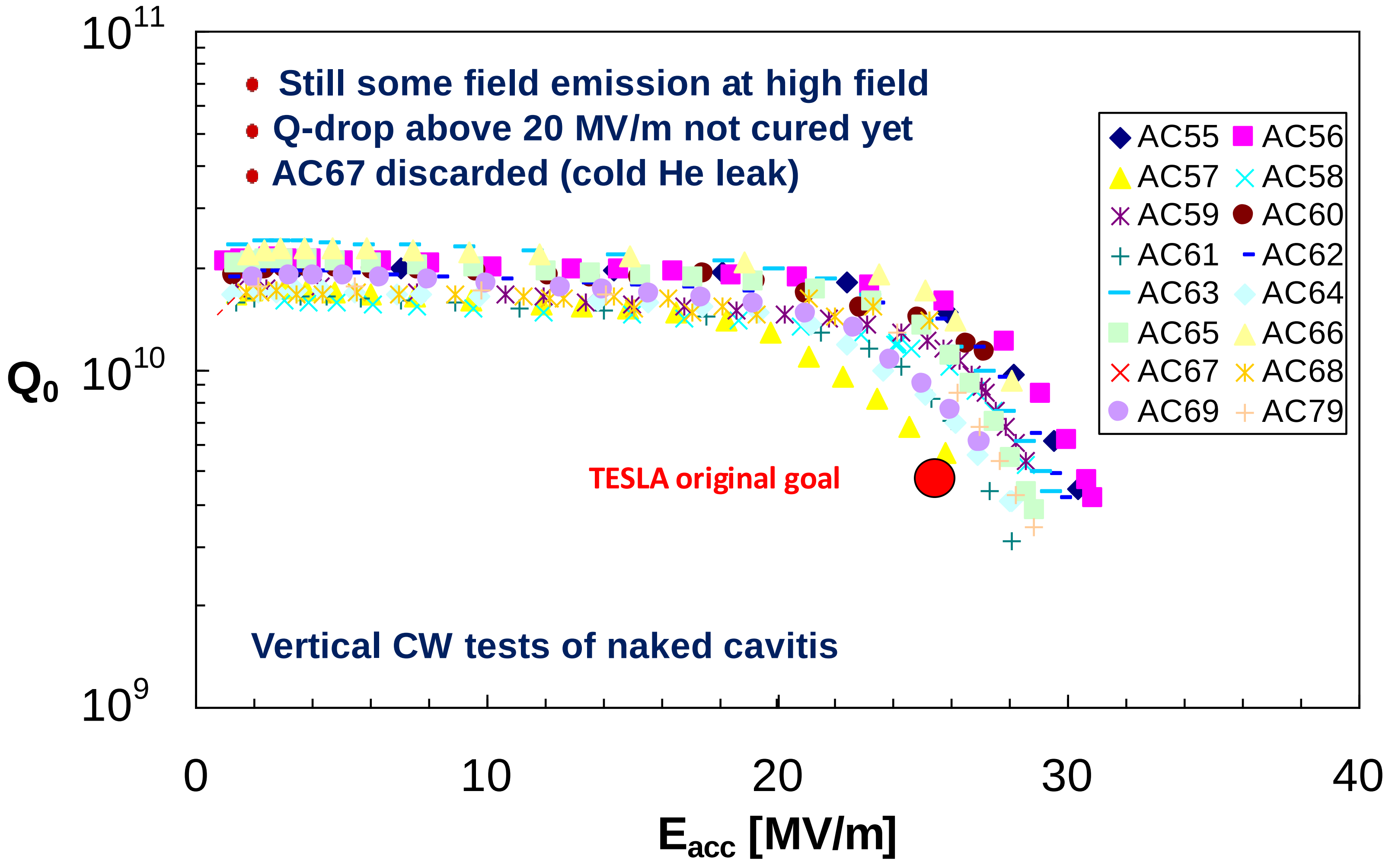


5-cell





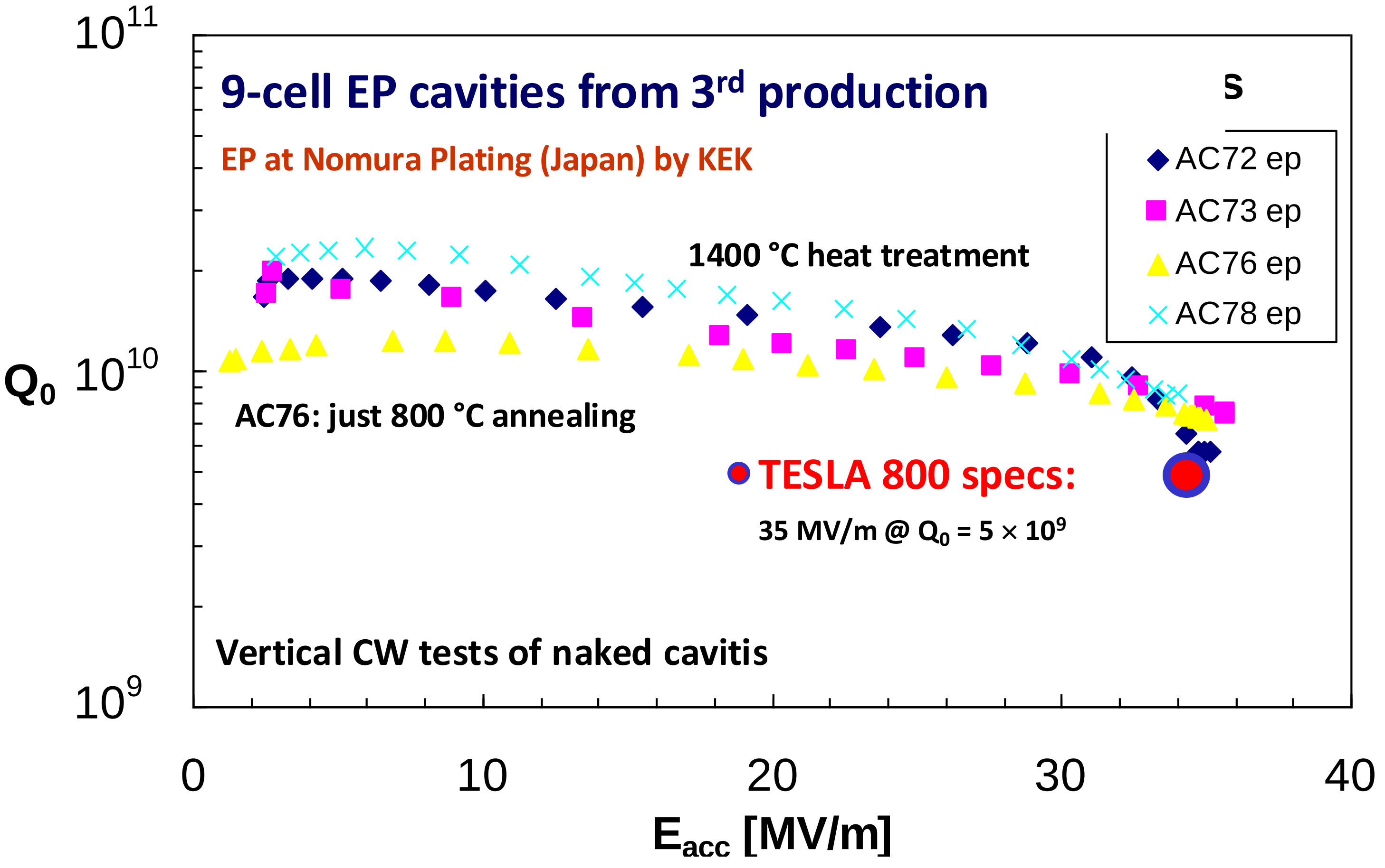
3^{rd} cavity production with BCP



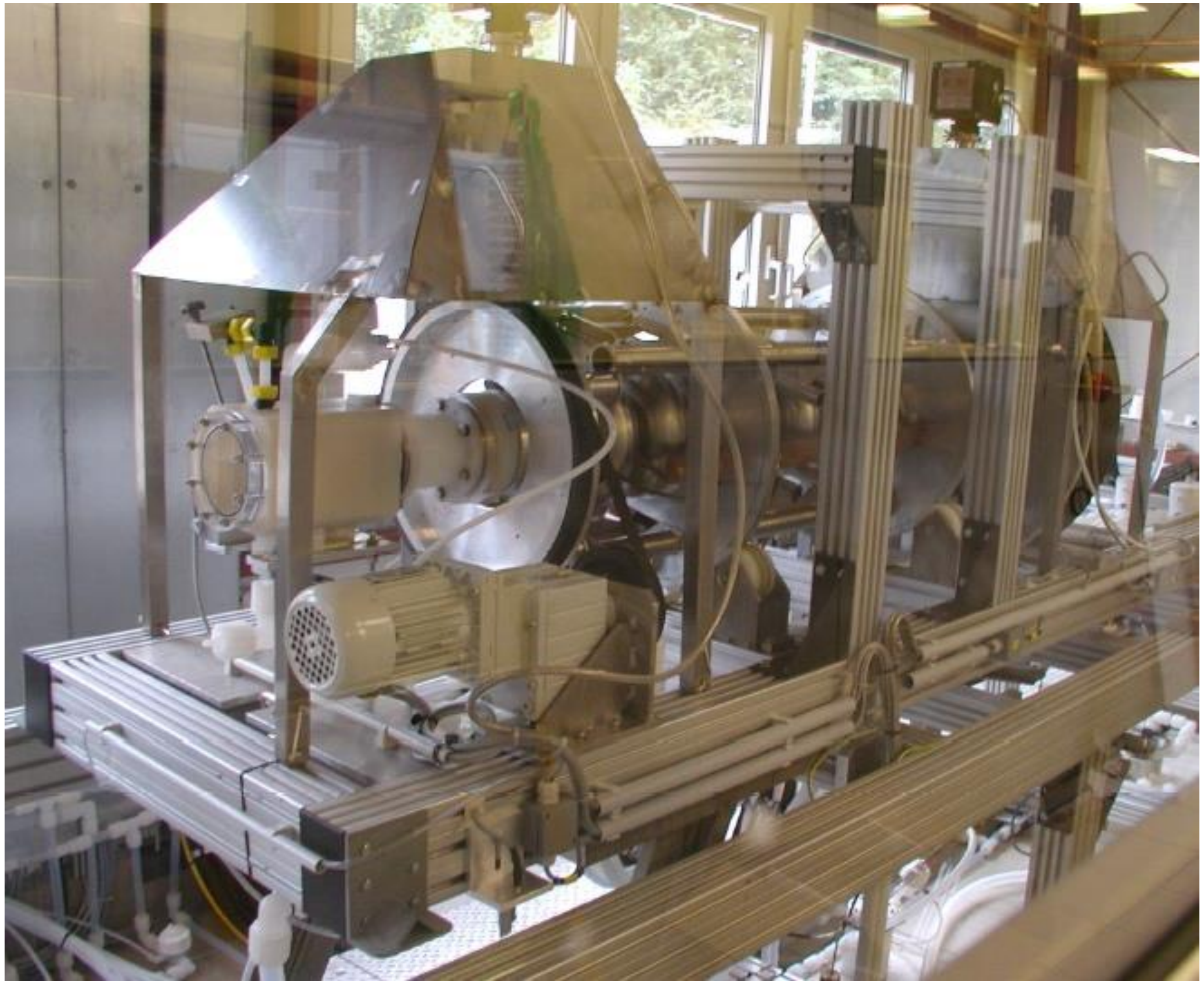
Further Improvement with EP

EP (Electro-Polishing) developed at KEK by Kenji Saito (originally by Siemens)

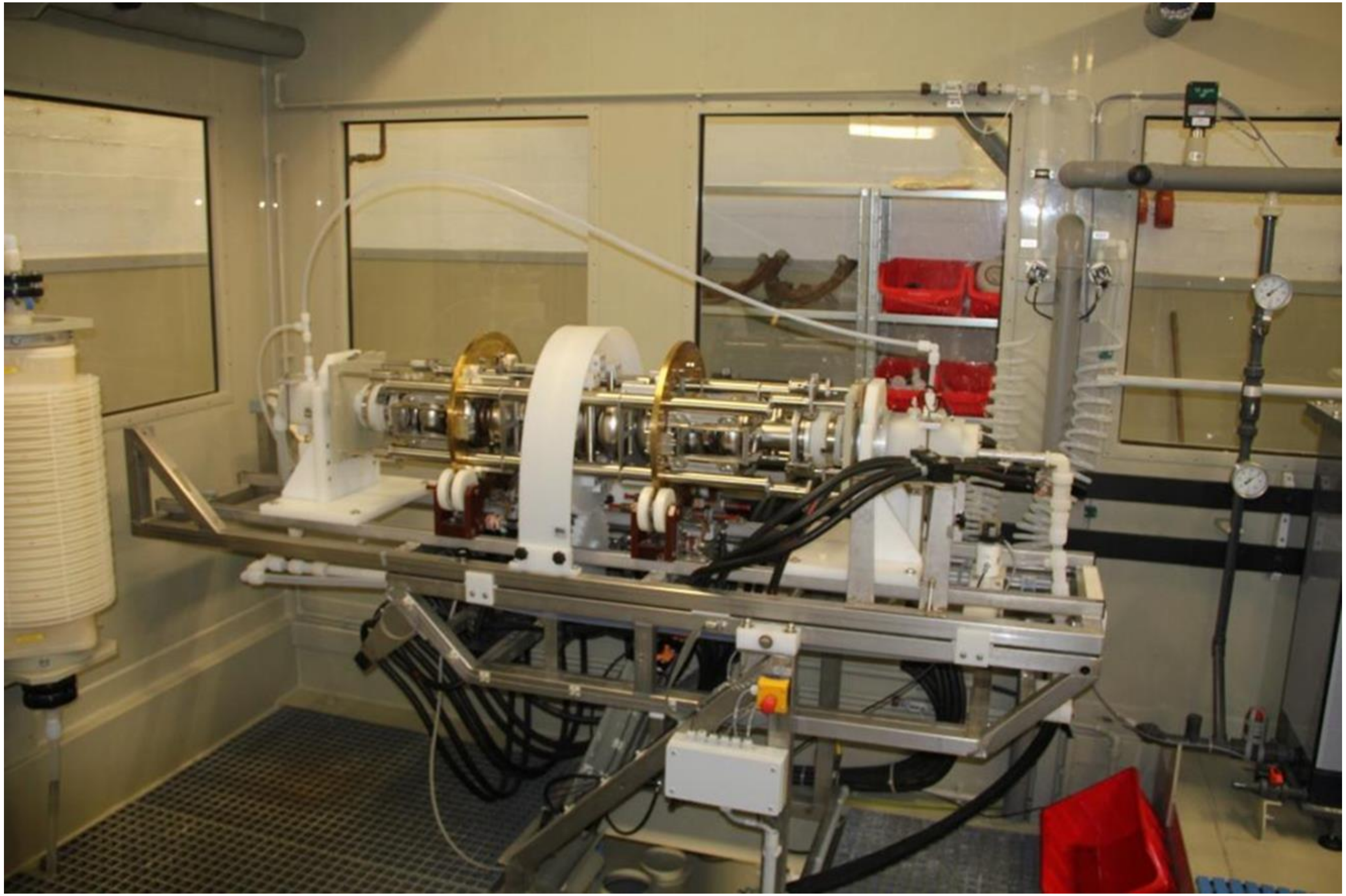
Coordinated R&D effort: DESY, KEK, CERN, CEA-Saclay & INFN LASA



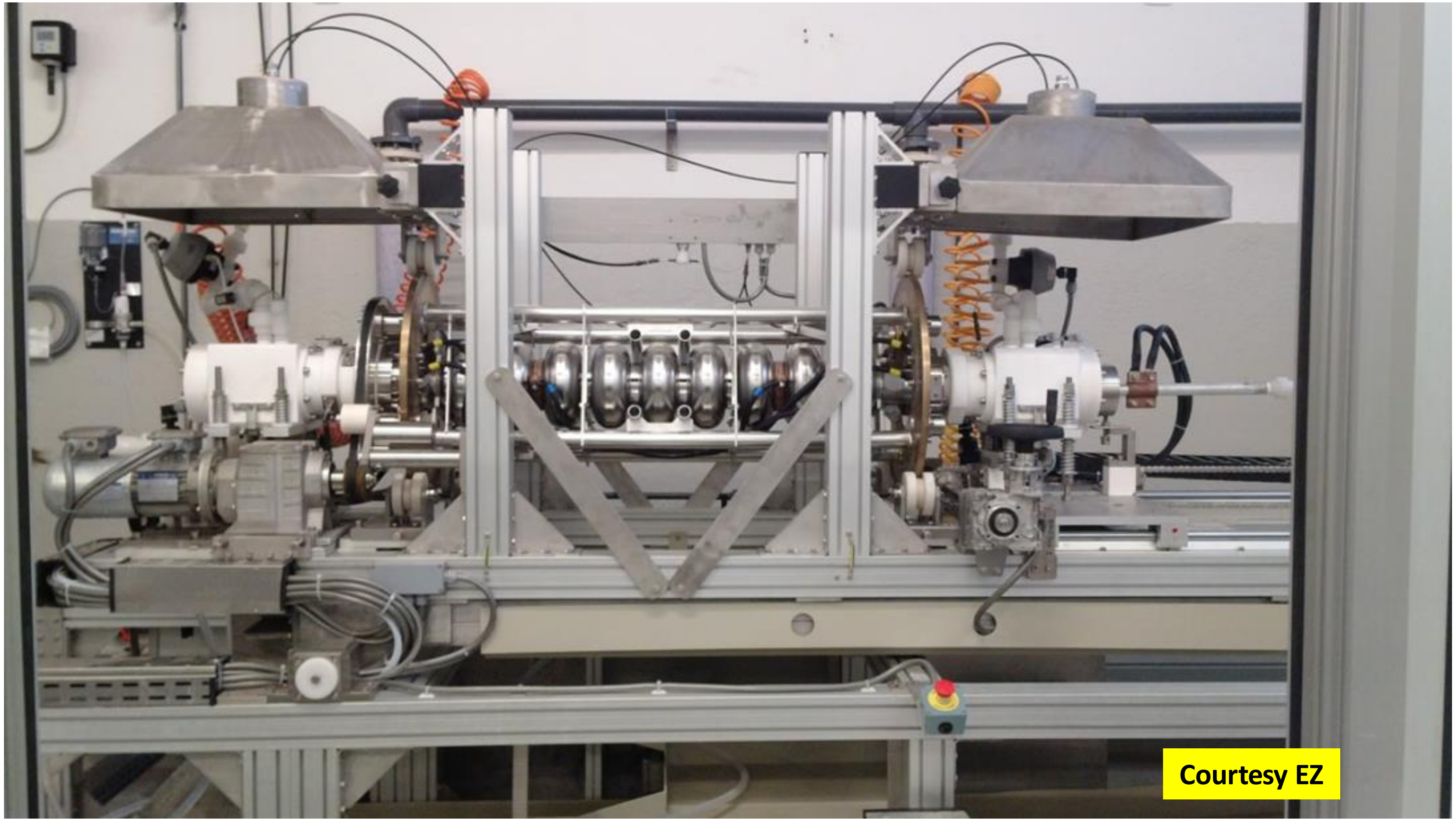
EP at DESY from the KEK Experience



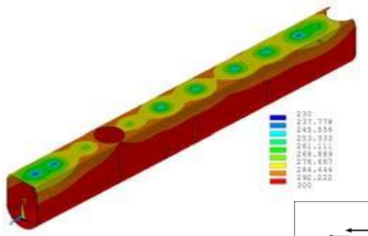
EP system at RI

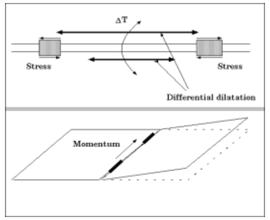


EP system at Zanon



Not Just Cavities: From Prototype to Cry 3



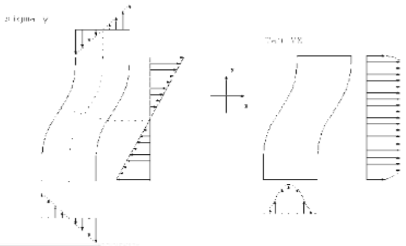


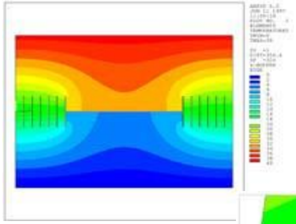
Extensive FEA modeling (ANSYS™) of the entire cryomodule

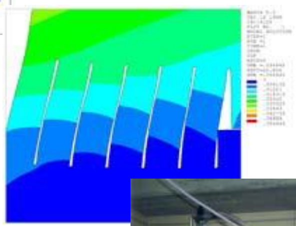
– Transient thermal analysis during cooldown/warmup cycles,
– Coupled structural/thermal simulations
– Full nonlinear material properties

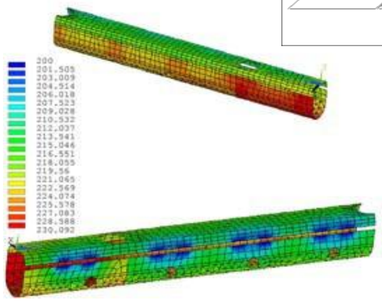
Detailed sub-modeling of new components and Laboratory tests

– Finger-welding tests at ZANON
– Cryogenic tests of the sliding supports at INFN-LASA

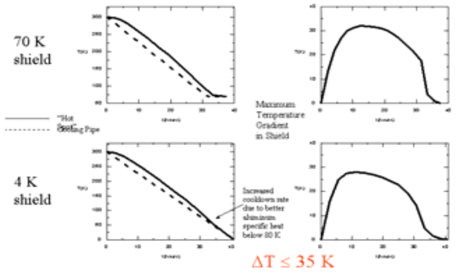


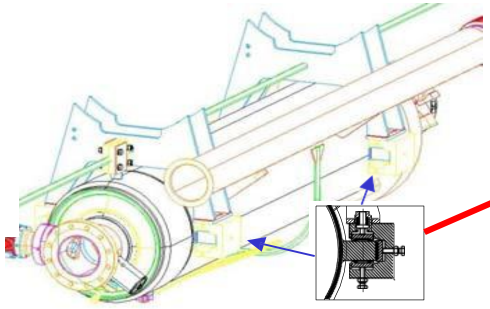


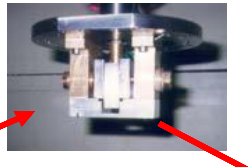




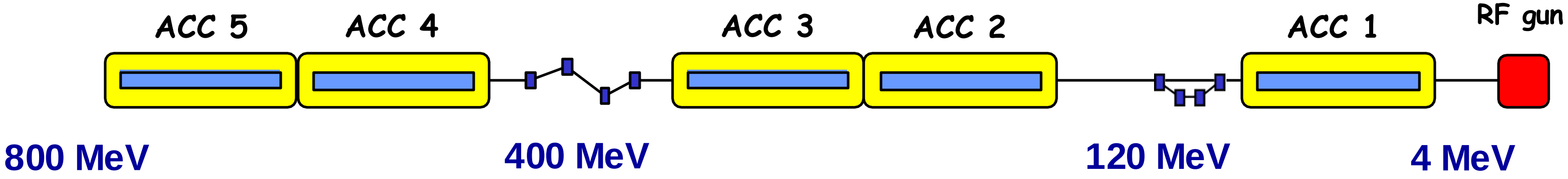
Welded Shields





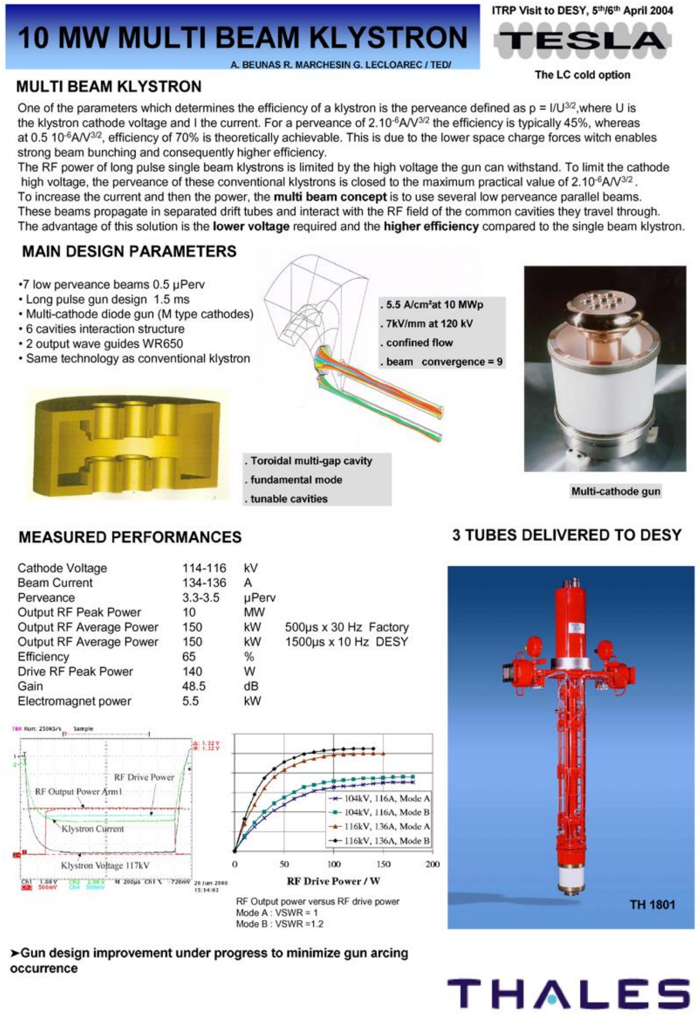


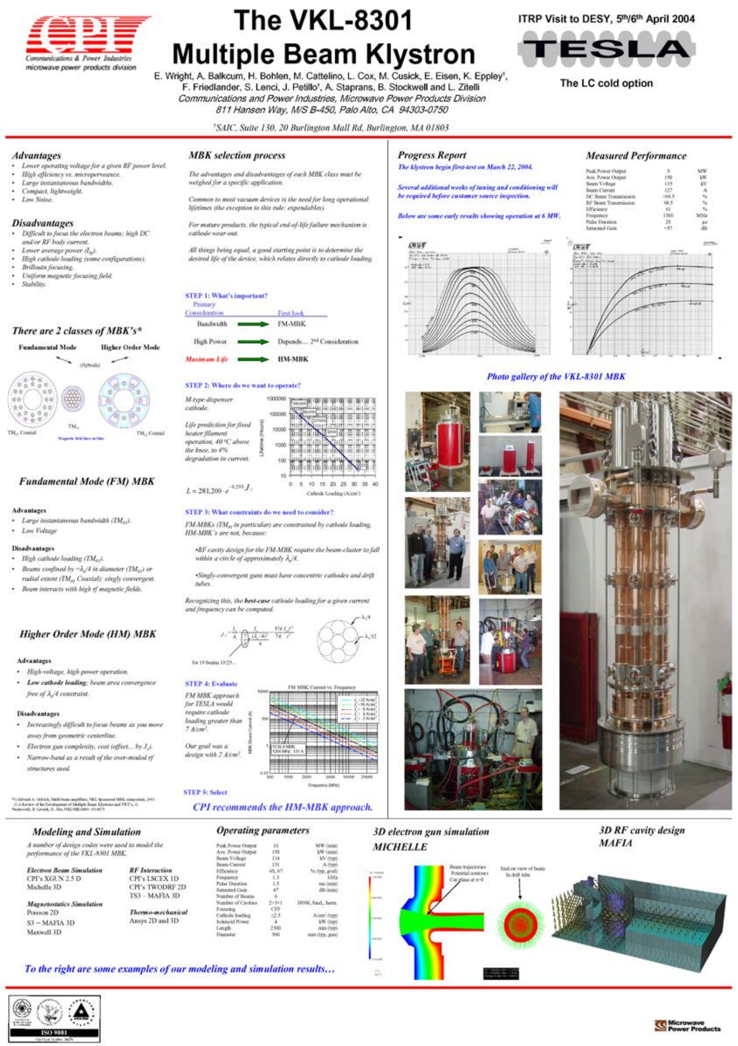
Cryomodule Evolution in TTF-II

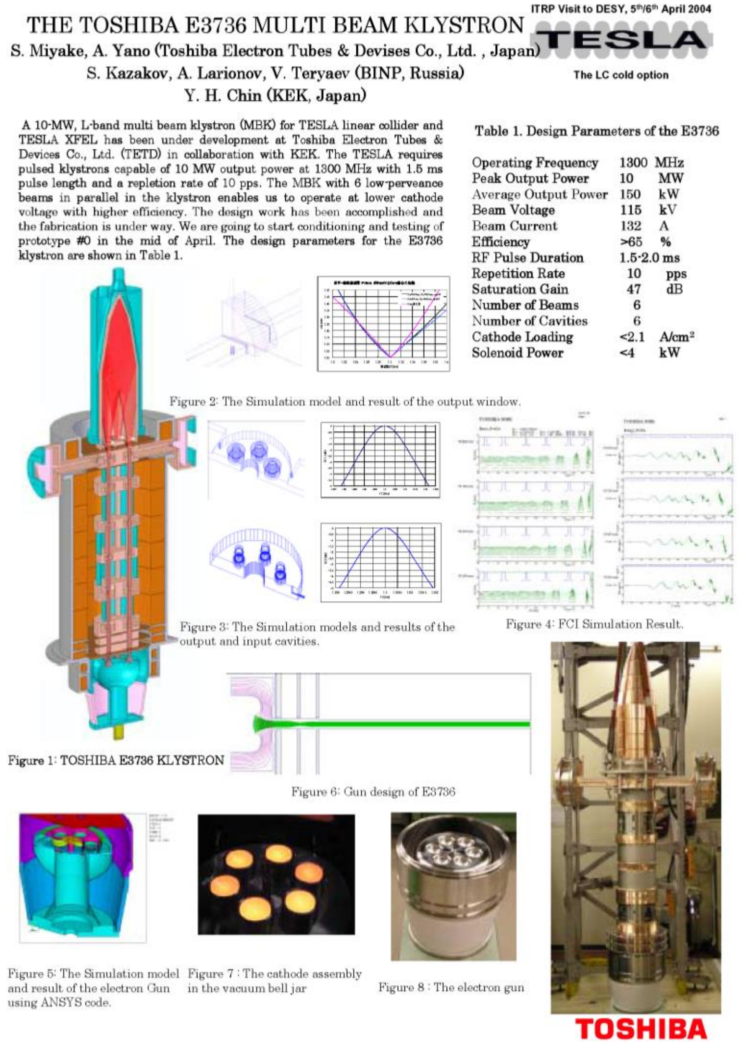


ILC Acc. Workshop
16 August 2005

10 MW Klystrons Developped by Industry





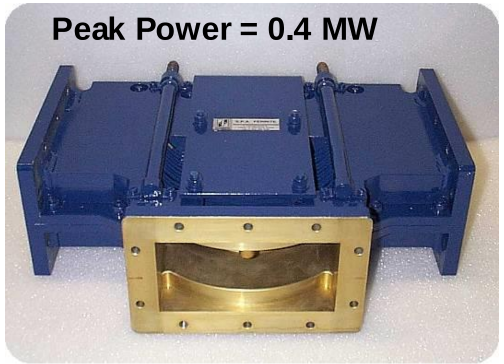


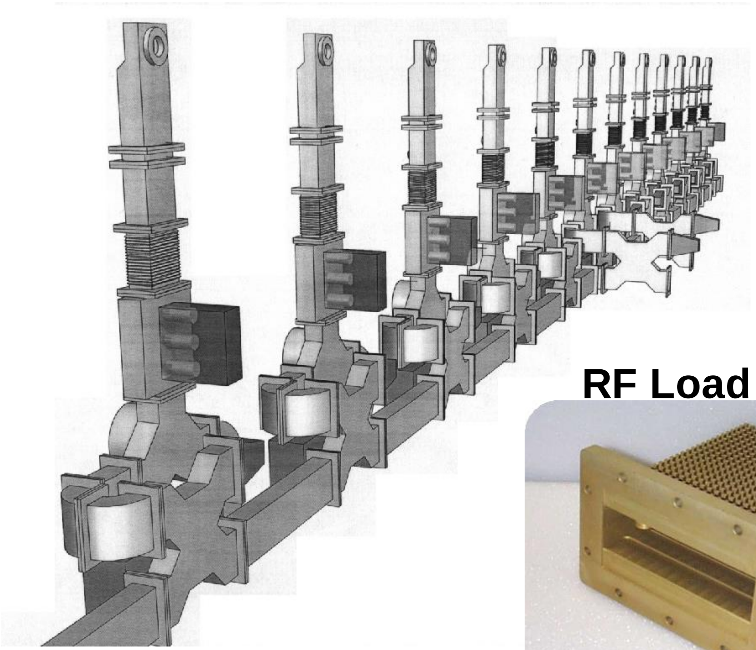
RF Waveguide Components @ 1.3 GHz

3 Stub Tuner (IHEP, Bejing, China)

E and H Bends (Spinner)

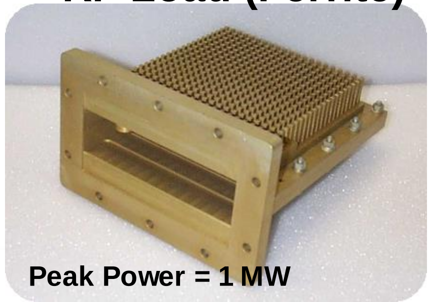
Circulator (Ferrite)



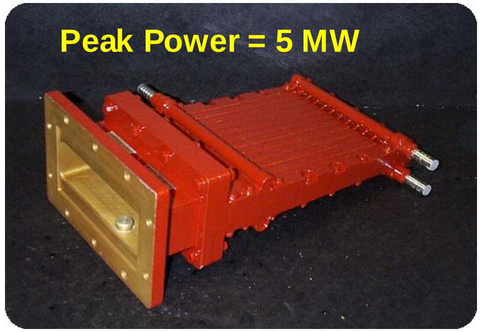


Hybrid Coupler (RFT, Spinner)

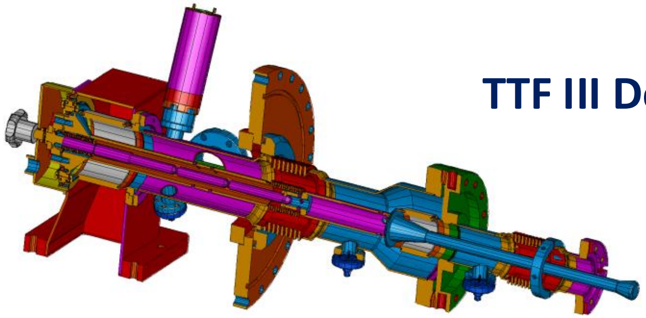
RF Load (Ferrite)



RF Load (Ferrite)

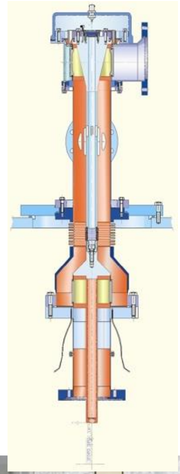


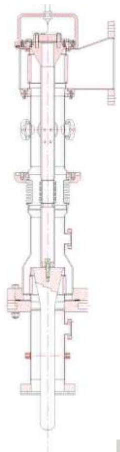
Ancillaries: Coupler R&D at LAL-Orsay

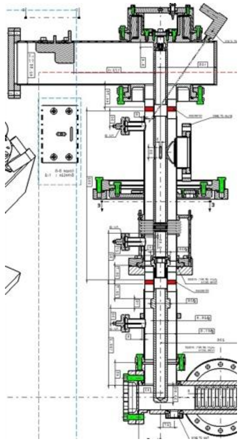


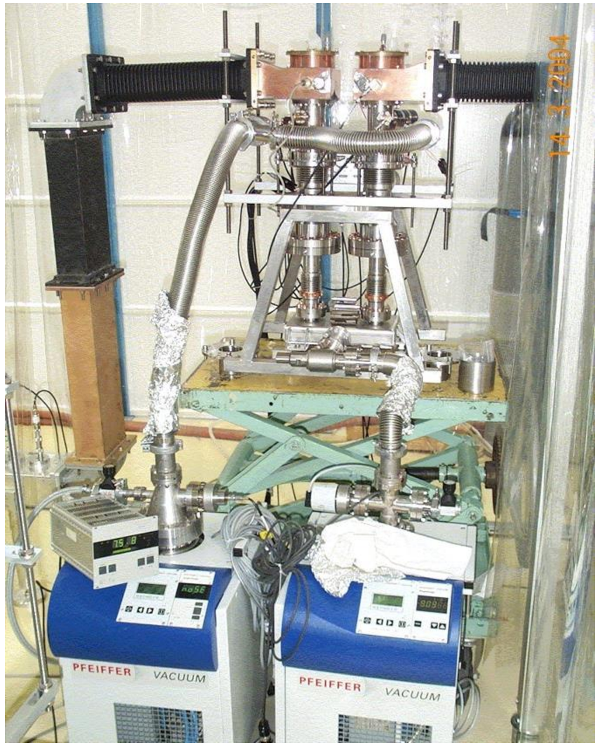
TTF III Design

Alternative Designs







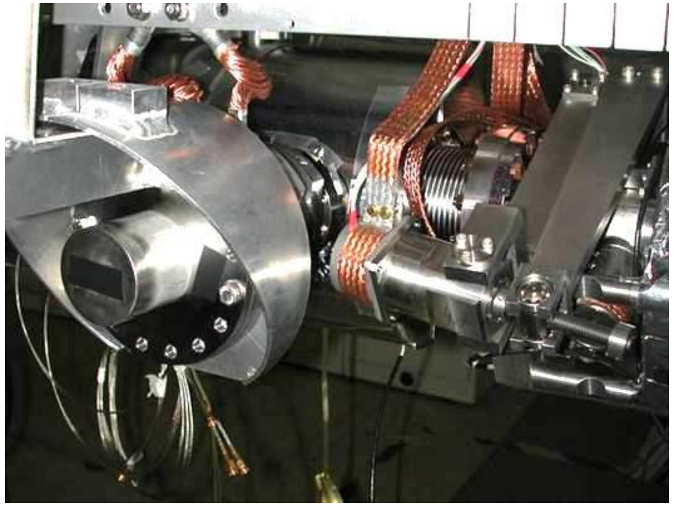


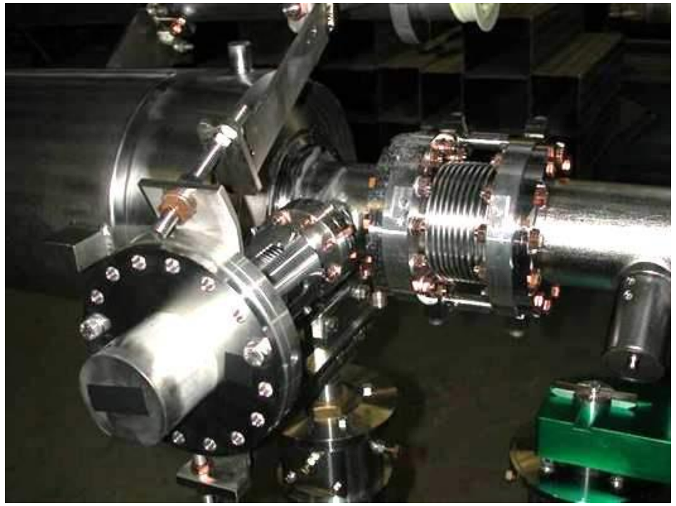
High Power Coupler Test Stand

Clean room assembly

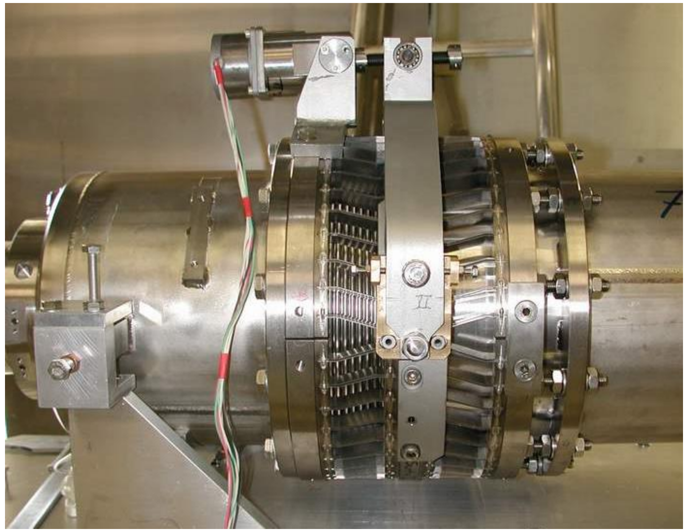
Ancillaries: Cavity Tuners

The Saclay Tuner in TTF

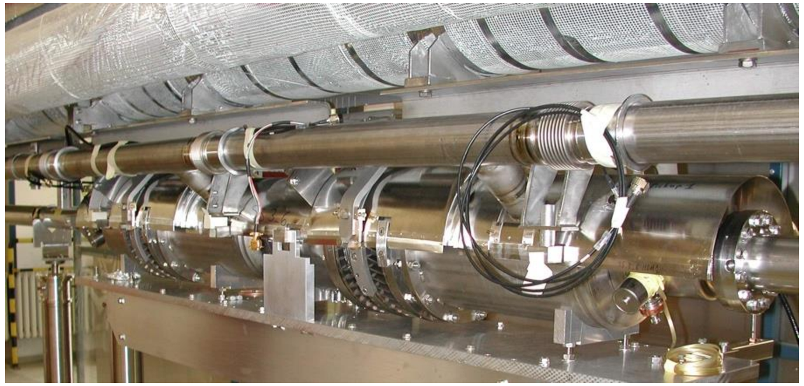




The INFN Blade-Tuner

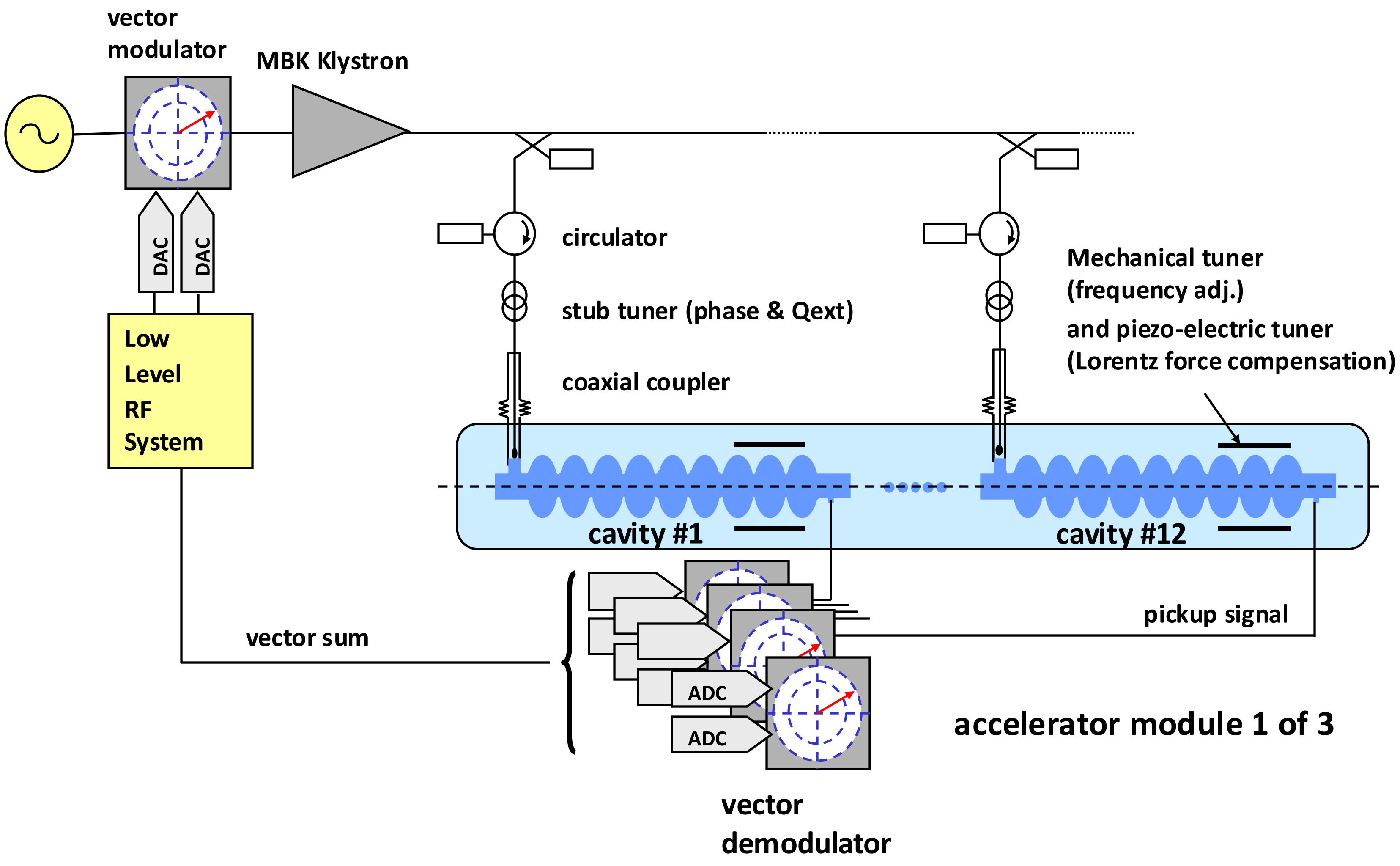


Successfully operated with superstructures

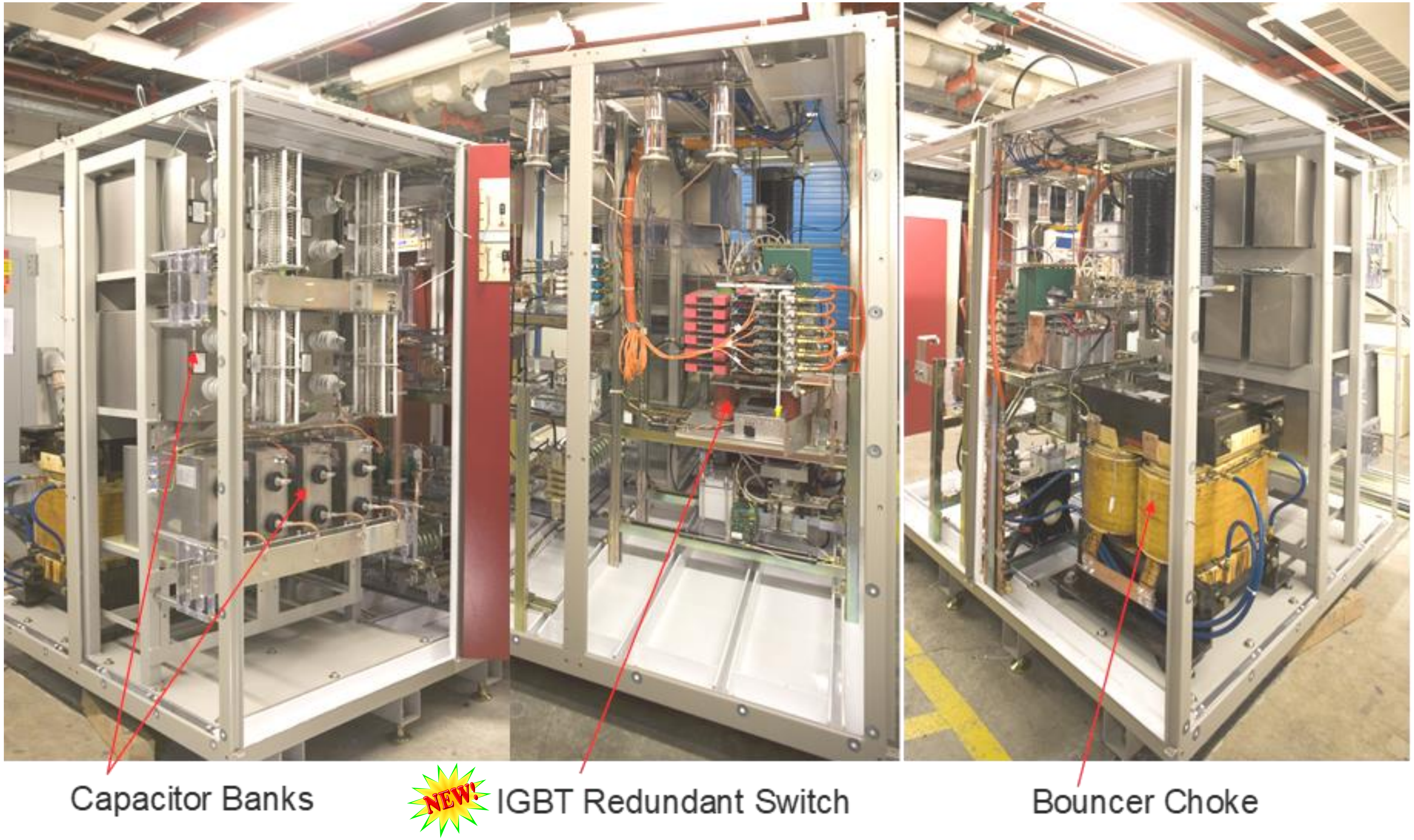


RF Distribution: the TESLA RF Unit

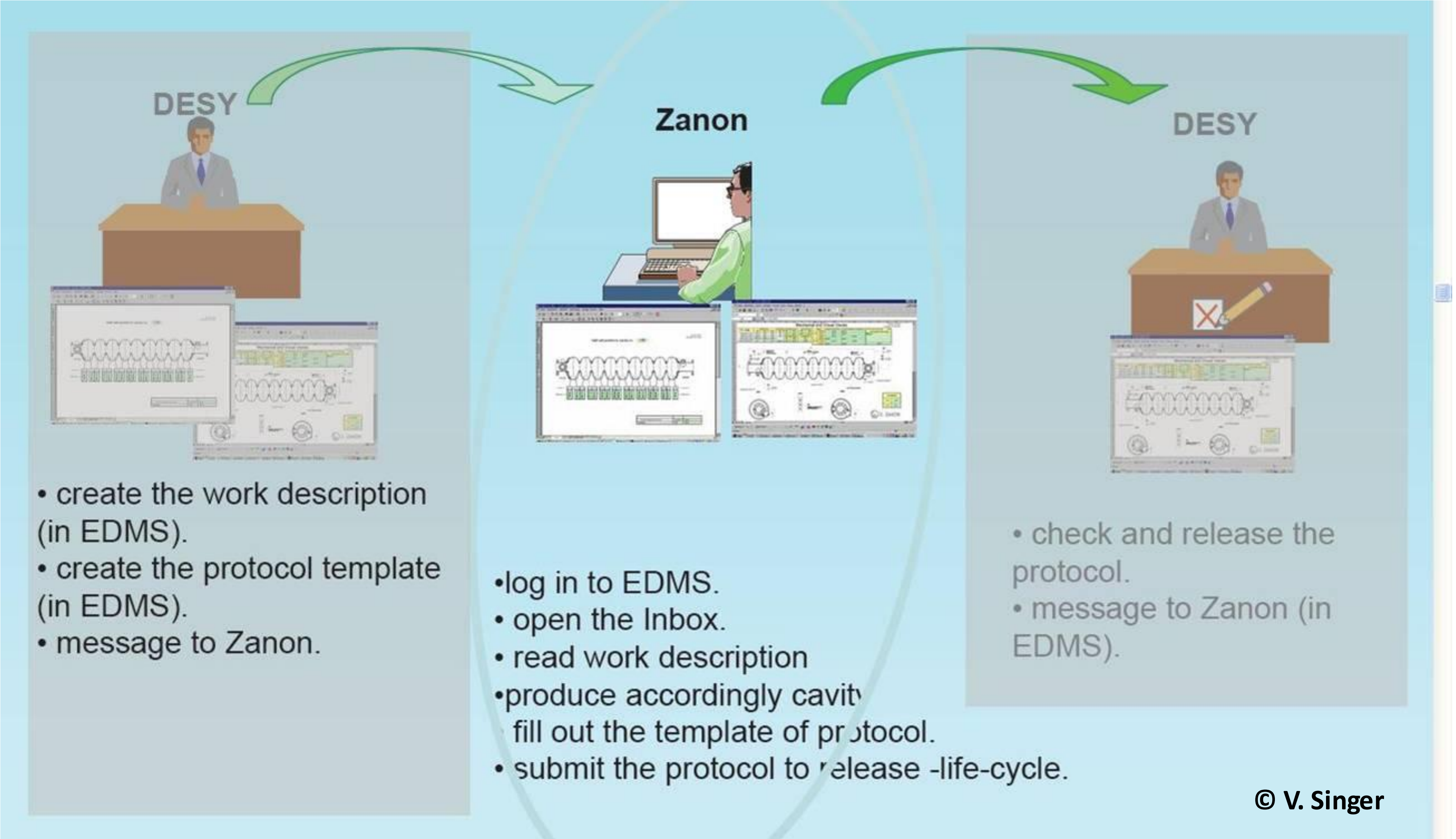
1 klystron for 3 accelerating modules, 12 nine-cell cavities each



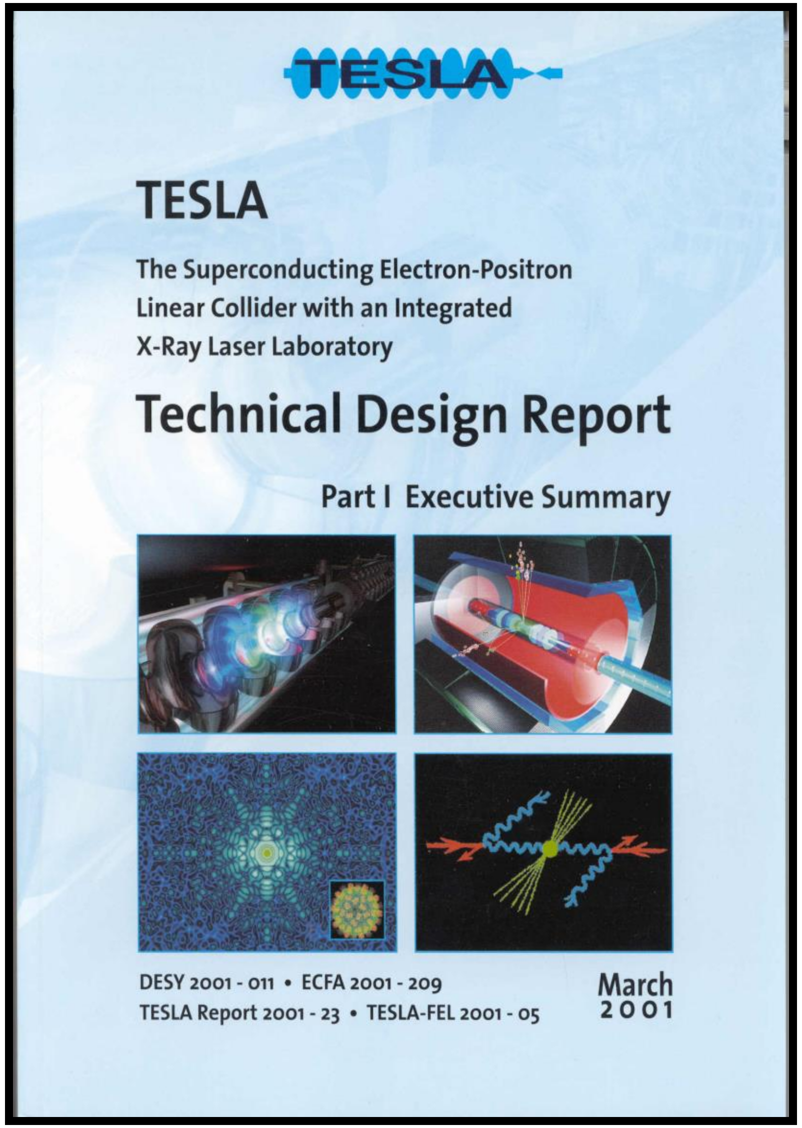
Pulse Transformer Modulator Layout

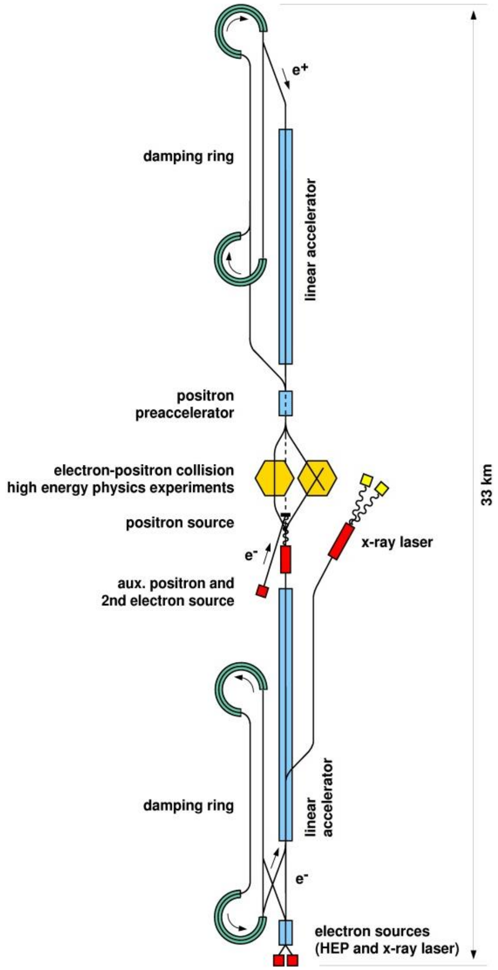


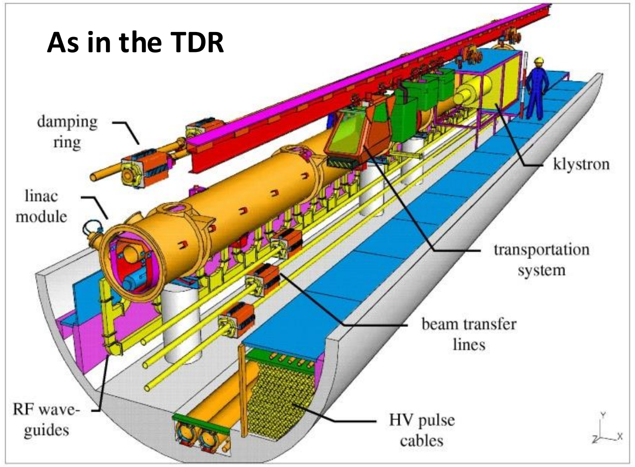
New QC tools in 4th Production

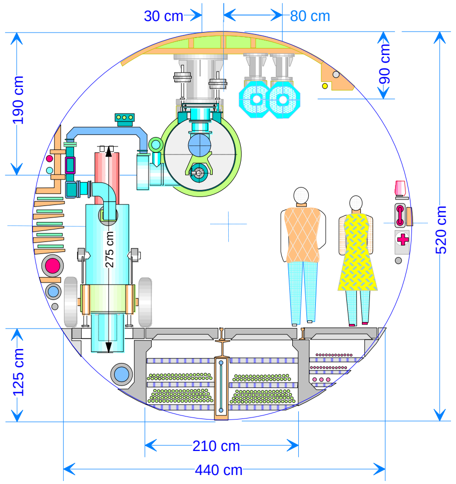


TESLA Technical Design Report: March 2001



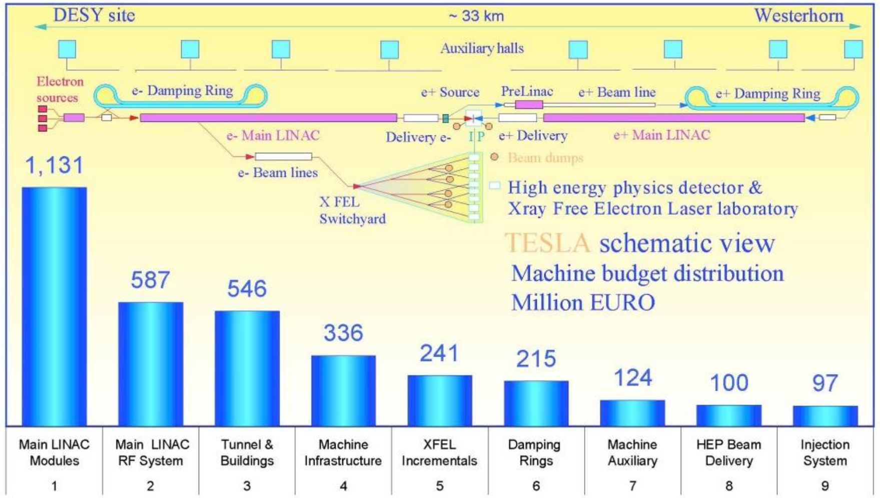


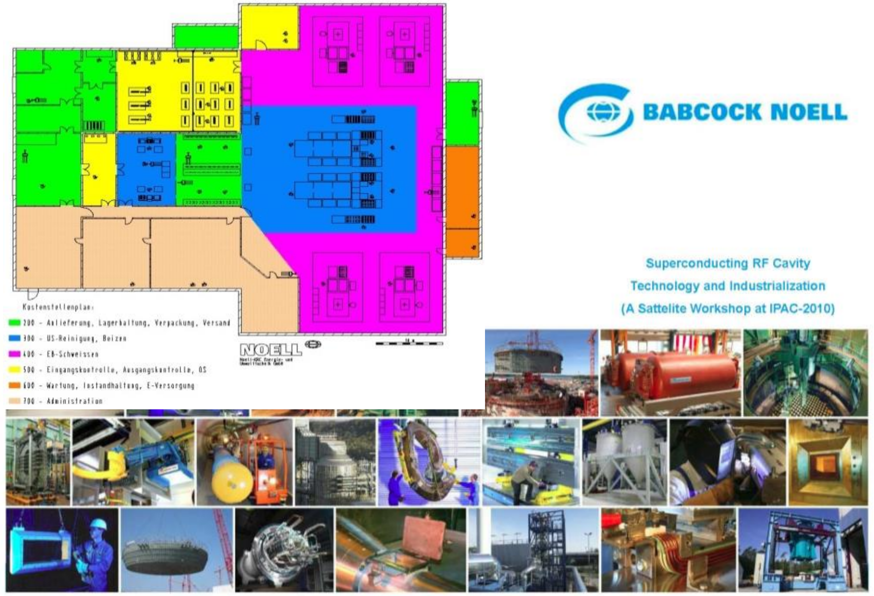


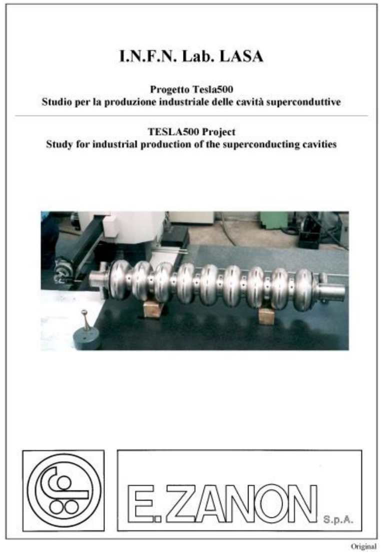


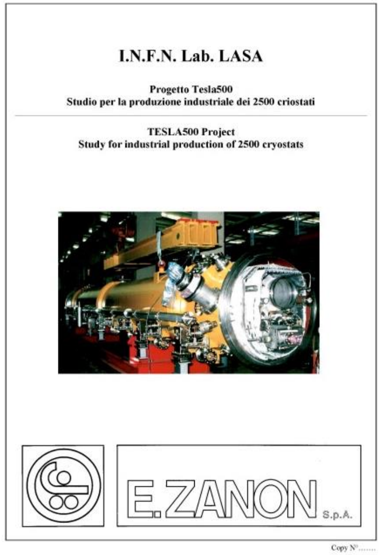
Updated tunnel cross section

Industrial Studies for TESLA TDR & E-XFEL







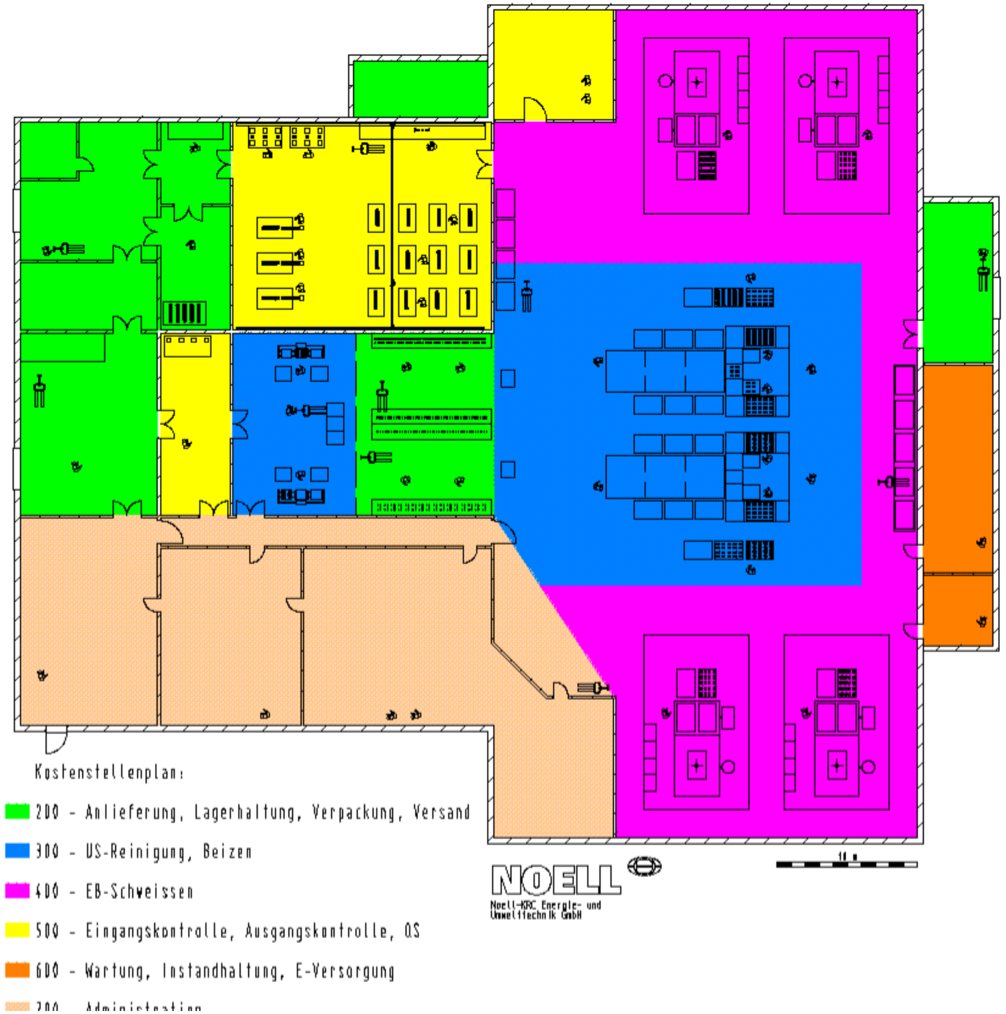


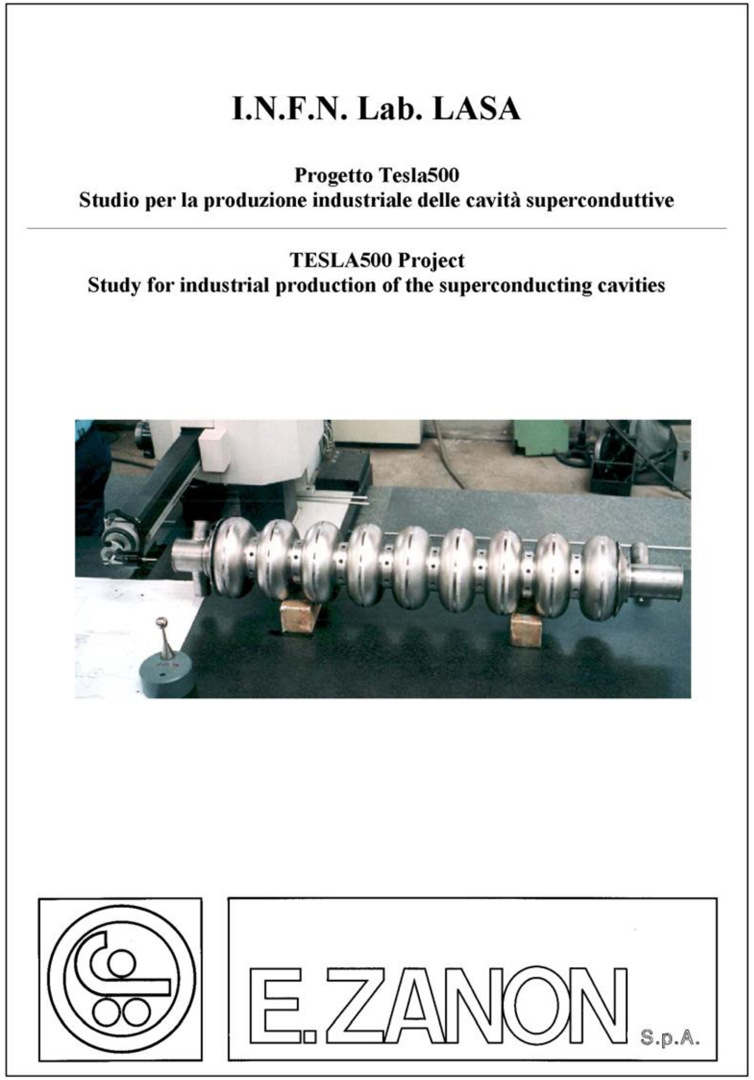
Overview on industrial studies for superconducting linacs (TESLA, XFEL,CARE), status dec.05, D.Proch

#	Subject	main issues	design	fabrication	cost	Contract	Status
1	Nb RRR 300	500 to of Nb sheet production		X	X	DESY	finished
2	Cavity fabrication	20000 cavities, welding		X	X	DESY	finished
3	Cavity fabrication	1000 cavities, welding		X	X	DESY	finished
4	Cavity fabrication	20000 cavities, hydroforming		X	X	DESY	finished
5	Cavity processing	20000 cavities, VT test, 1400°C, BCP		X	X	DESY	finished
6	Module assembly I	Assembly of 20000 cavities		X	X	DESY	finished
7	Cavity processing	Substitute BCP by EP, 1000 cavities		X	X	XFEL	in preparation
8	Module assembly II	Improvements to study 6, 1000 cavities	X	X	X	XFEL	started
9	Input coupler	improvement to TTF3 design, 1000 couplers	X	X	X	XFEL	in preparation
10	EP	Industrial aspects of EP		X	X	CARE	in preparation
11	Improvement of components	Reliability aspects of critical components	X	X		CARE	in preparation
12	Squid scanner	Principle layout, prototype	X	X		CARE	finished

Cavity Fabrication Industrial Studies

Production Plan for 20,000 cavities





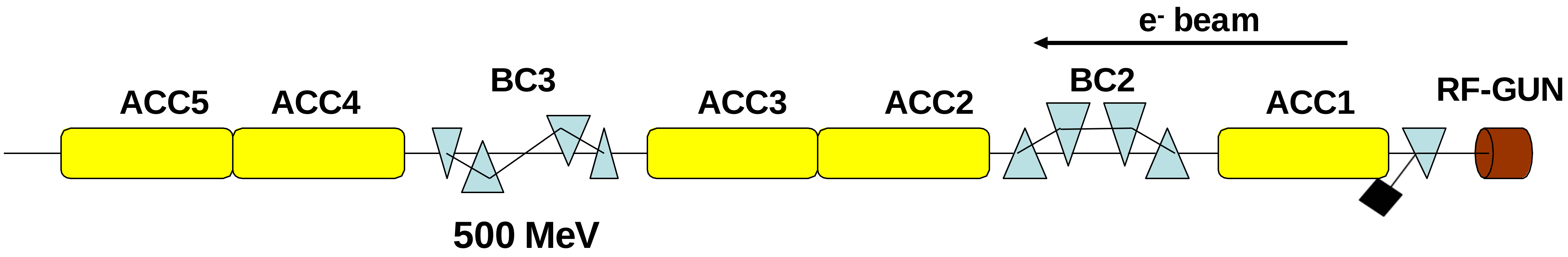
I.N.F.N. Lab. LASA

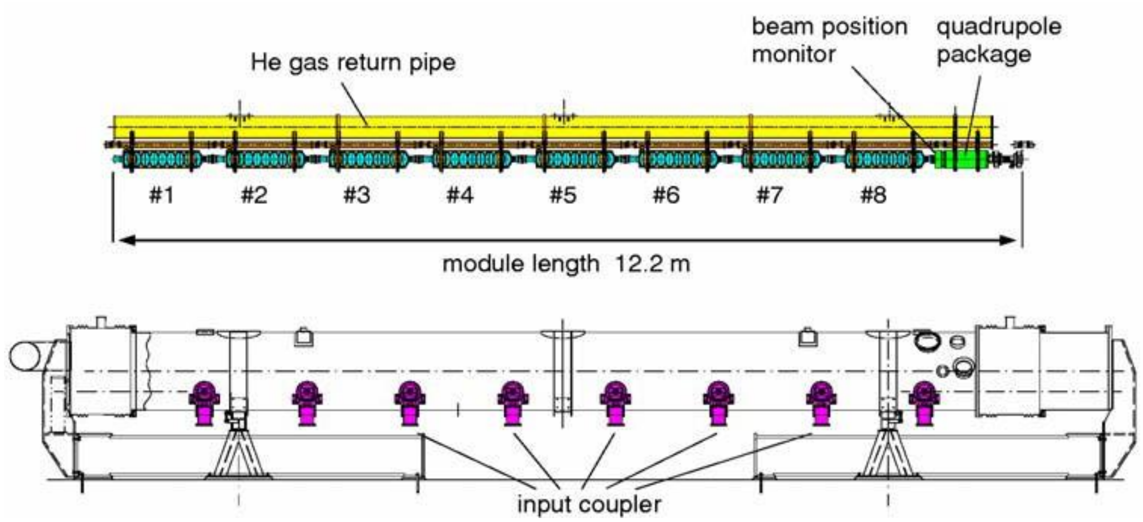
Progetto Tesla500
Studio per la produzione industriale delle cavità superconduttive

TESLA500 Project
Study for industrial production of the superconducting cavities

E.ZANON S.p.A.

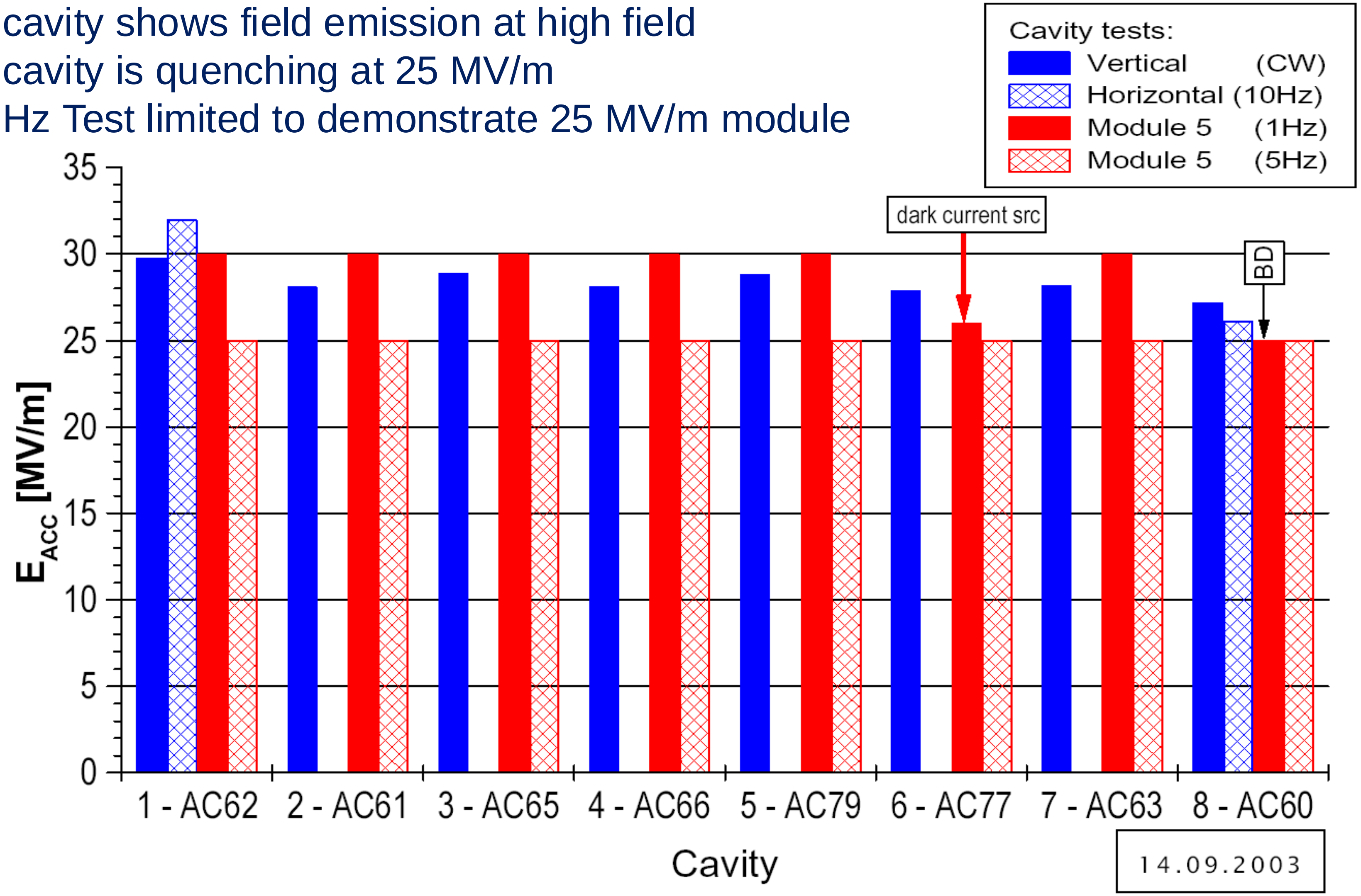
TTF2 as XFEL Injector Prototype





Outstanding Results with module # 5

6 cavities exceed 30 MV/m
1 cavity shows field emission at high field
1 cavity is quenching at 25 MV/m
5 Hz Test limited to demonstrate 25 MV/m module



TESLA/XFEL Milestones

July 1990 – 1° International TESLA Workshop @ Cornell University

February 1992 – 1° TESLA Collaboration Board Meeting @ DESY

March 1993 - **"A Proposal to Construct and Test Prototype Superconducting RF Structures for Linear Colliders"**

March 1995 -TESLA Test Facility Linac Design Report

SASE FEL included in TESLA → TTF 2

May 1996 – **first beam at TTF1**

March 2001 – **TESLA Technical Design Report with XFEL**
First SASE-FEL Saturation at TTF

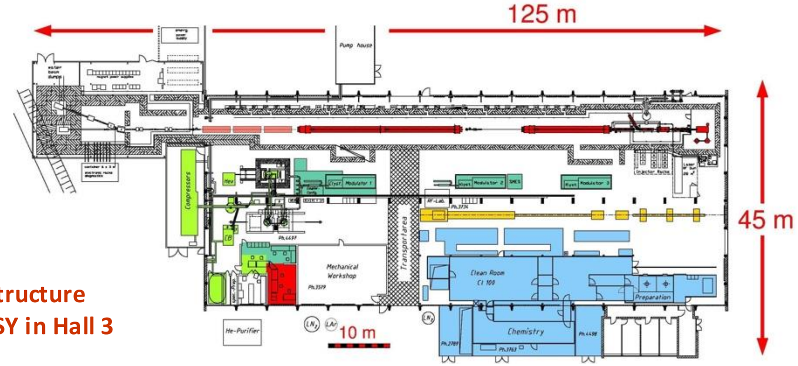
July 2002 – from the German Science Council: **Two independent projects: TESLA X-FEL** and **TESLA LC**

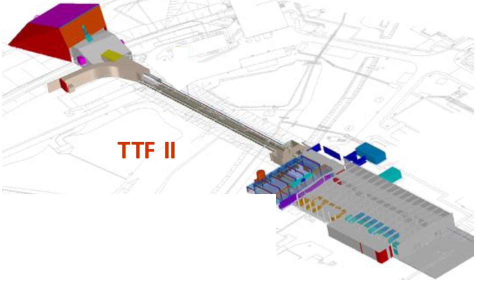
February 2003 –TESLA X-FEL proposed as an European Facility, **50% funding from Germany**

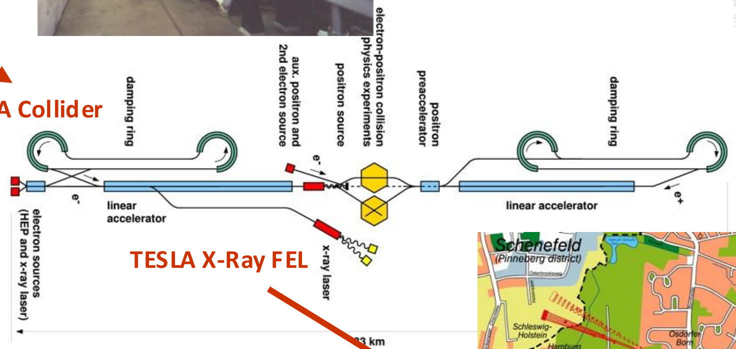
June 2004 – TTF II: First beam accelerated

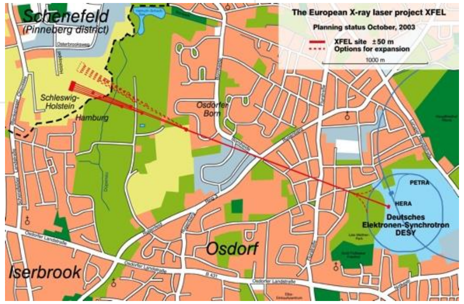
August 2004 – TESLA Technology chosen for ILC

June 2007 – European XFEL Project Starts



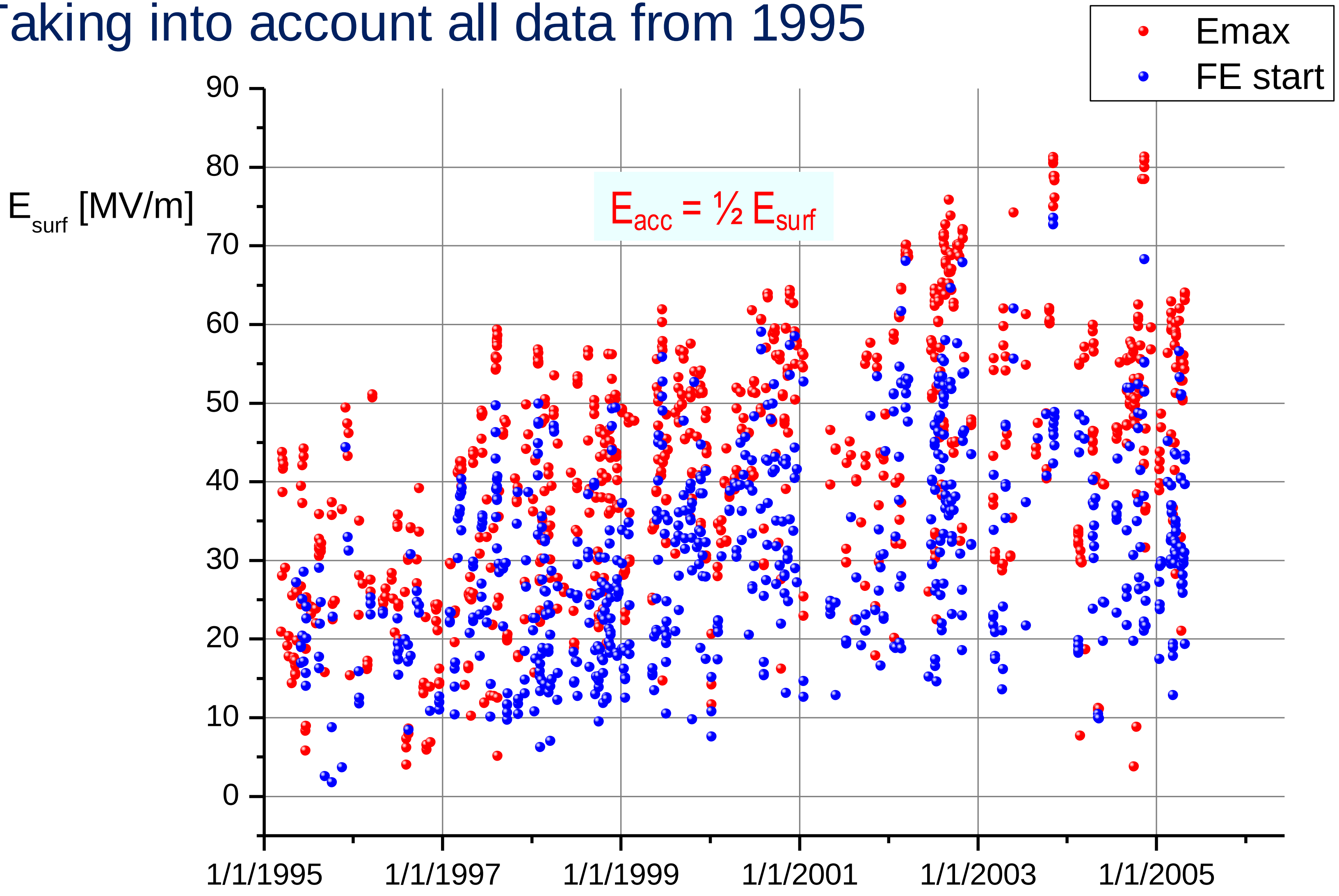






TTF: 10 years of experience

Taking into account all data from 1995



Contents

European XFEL Cavity Production - 1

At the end of the long prequalification process (TTF, FLASH, ILC,…)

Ettore **Z**anon, **EZ** & **R**esearch **I**nstruments, **RI**

were contracted at the **end 2010** to produce each

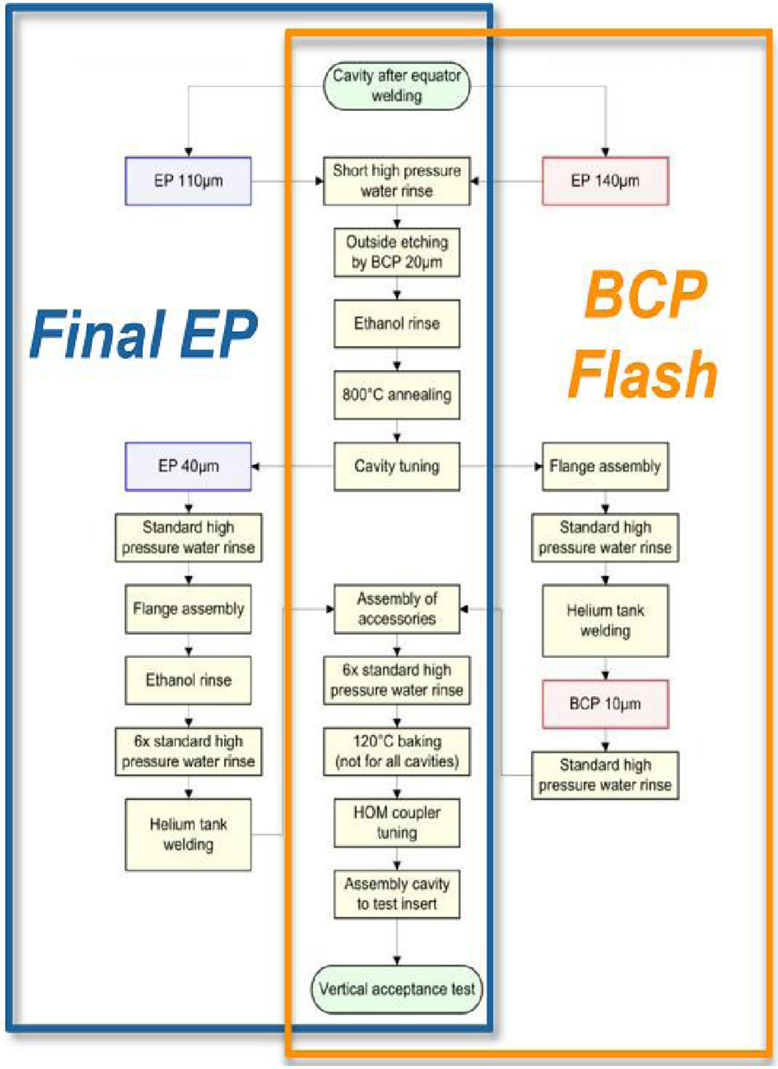
- **8 Cavities** for infrastructure rump/up and qualification
  4 Dummy CVs (DCV), 4 Reference CVs (RCV)
- **280 XFEL type series cavities (first 8 are PCV)**
  12 ILC HiGrade cavities

- **Additional 120 cavities allocated end 2012 to each companiy**
  Nb & NbTi supplied by DESY
- Production precisely following **detailed specifications** which also include the **exact definition of infrastructure** to be used (**build to print**)
- Final treatment after main EP: final **EP** for **RI** / flash **BCP** for **EZ**

European XFEL Cavity Production - 2

- **No performance guaranty by the vendors**, i.e. the risk of unexpected low gradient or field emission is taken over by XFEL/DESY (responsibility for re-treatment).
- **Goal**: average usable XFEL gradient **23.6 MV/m** at $Q_0 = 1 \times 10^{10}$, X-Rays <1×10^{-2} mGy/min
- First series cavities (PCV) **to be delivered end 2012 – begin 2013**
- All cavities to be delivered till **end 2014 – begin 2015**
- Delivery rate: about **8 CVs/week** (4/each vendor)
- Supervision of the CV production: **DESY & INFN/LASA**

Treatments as from Experience on Prototype



Prior surface treatment.

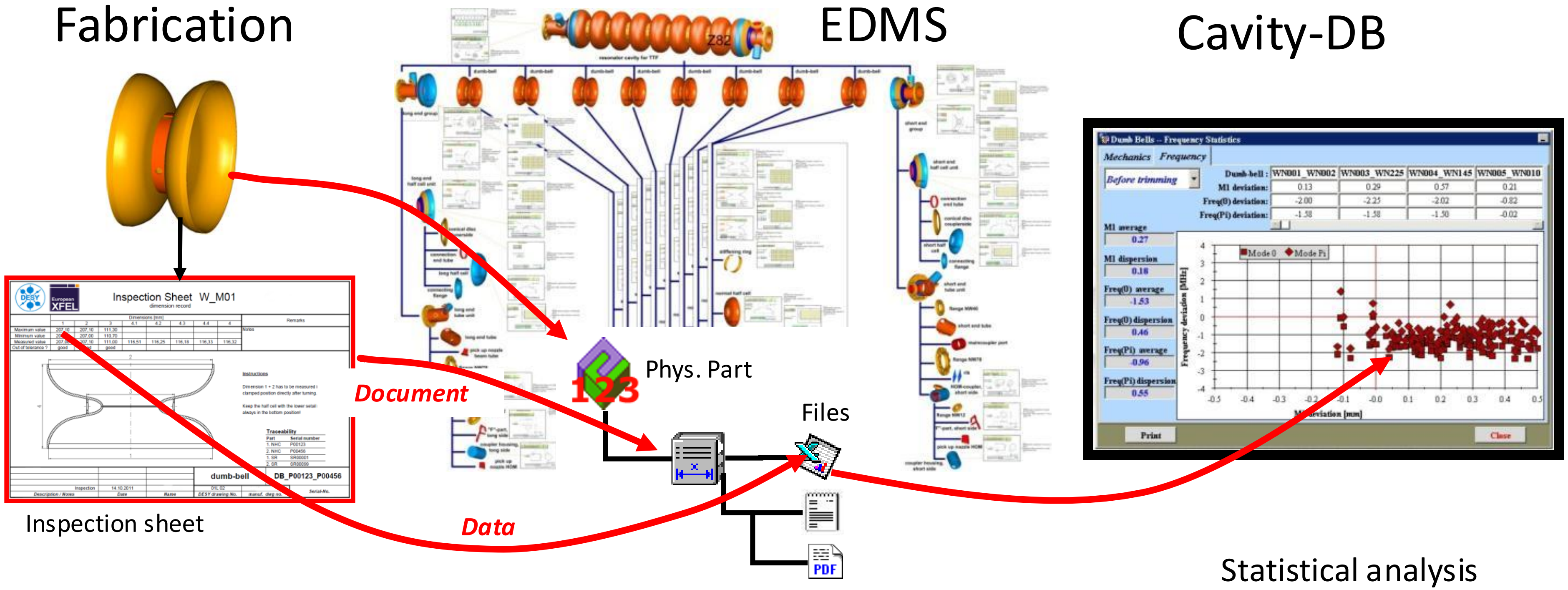
EP 110-140 µm (main EP), ethanol rinse, outside BCP, 800°C annealing, tuning

Final surface treatment - two alternative options

1. Final EP of 40 µm, ethanol rinse, high pressure water rinsing (HPR) and 120°C bake
2. Final BCP of 10 µm (BCP Flash), HPR and 120°C bake.

Integration of the helium tank, assembly of HOM, pick up and high Q antennas before vertical RF test

e-Documentation in EDMS - Data Bank



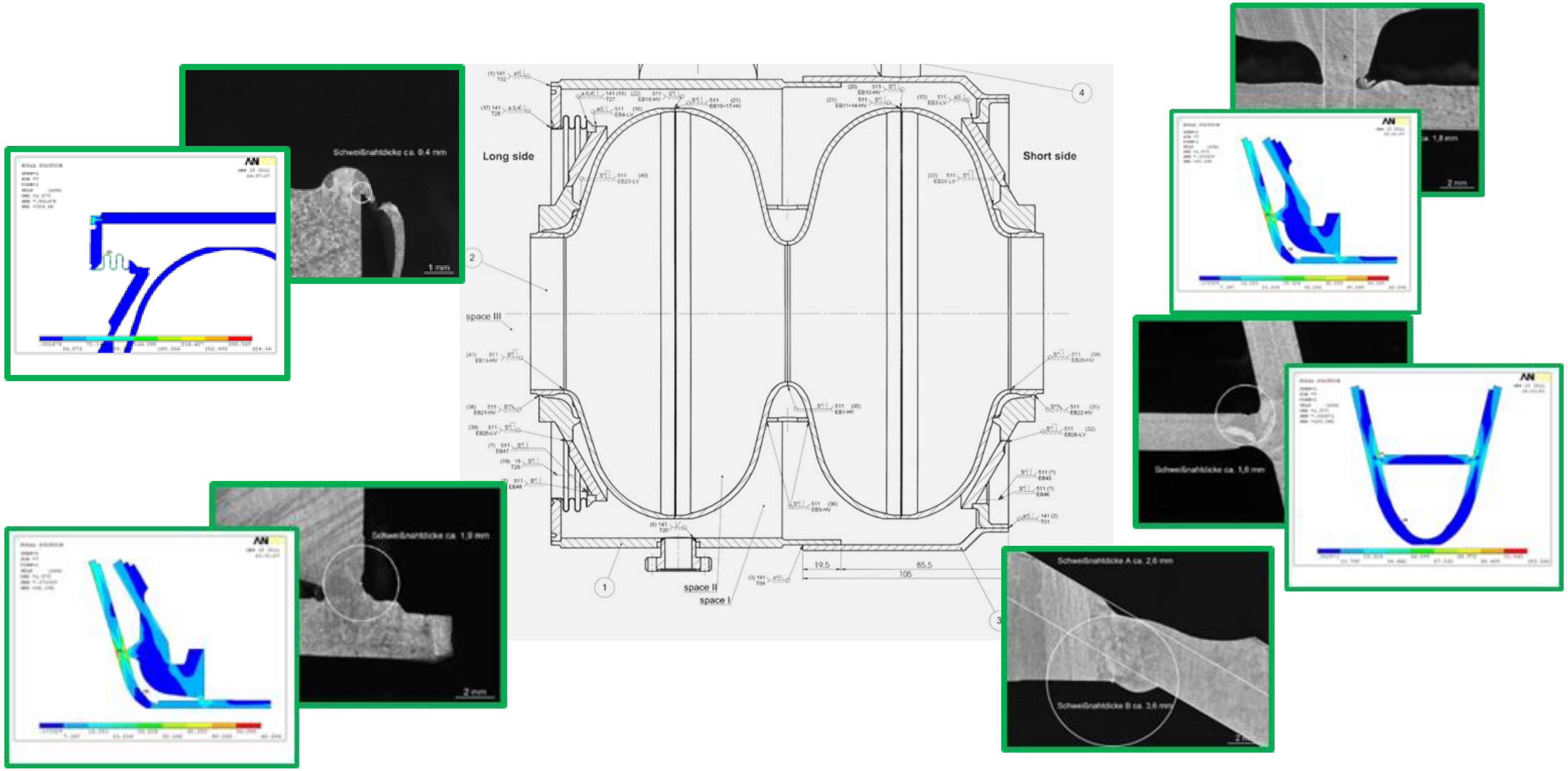
Inspection sheets for QM documentation

Fabrication structure.
Subassembly parts related.
Procedure related

- **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)

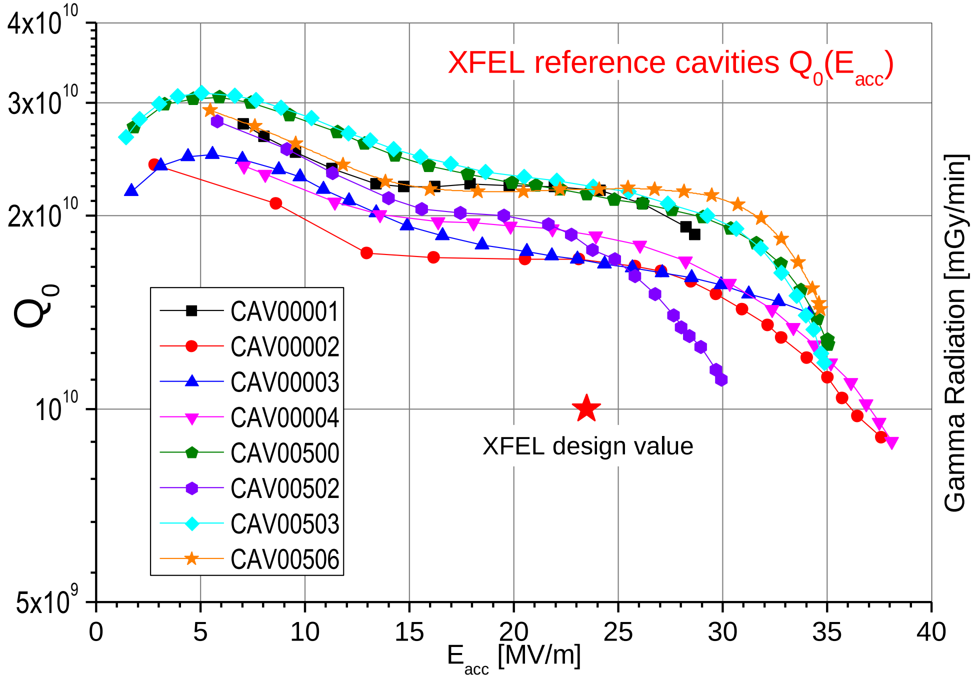
PED Activities and TUEV Control

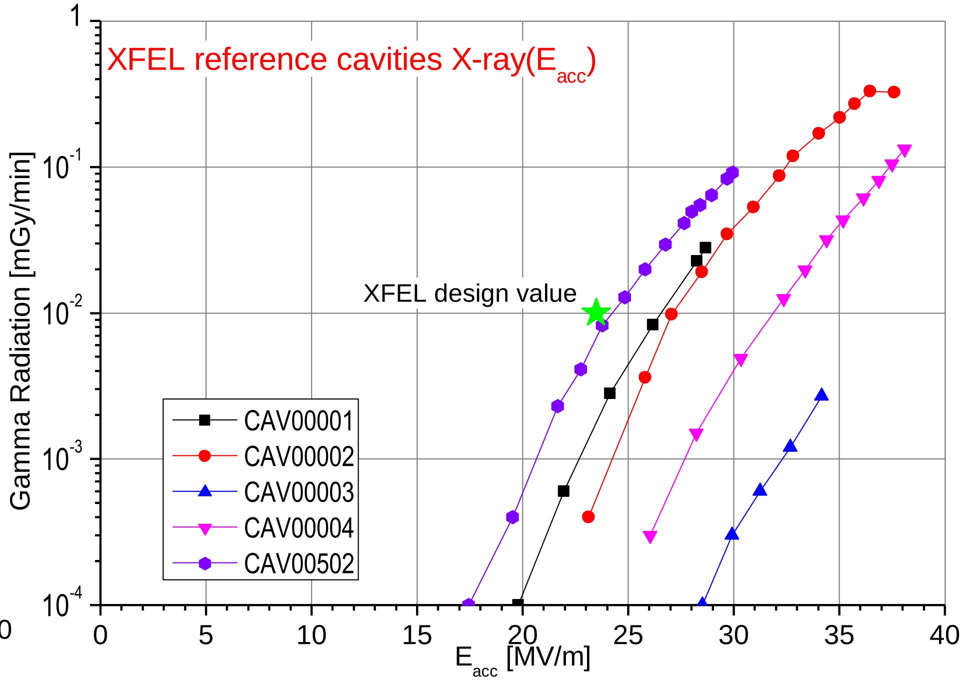
Test piece (TP) is composed by 2 cell with helium vessel, without end groups, representing all pressure bearing parts and welds. It is built using exactly the same manufacturing methods and welding parameters that will be later used for production. **Two EBW machines/company. Then two test pieces had been built.**



Good performance of reference cavities

8 RCVs: acceptance test successful





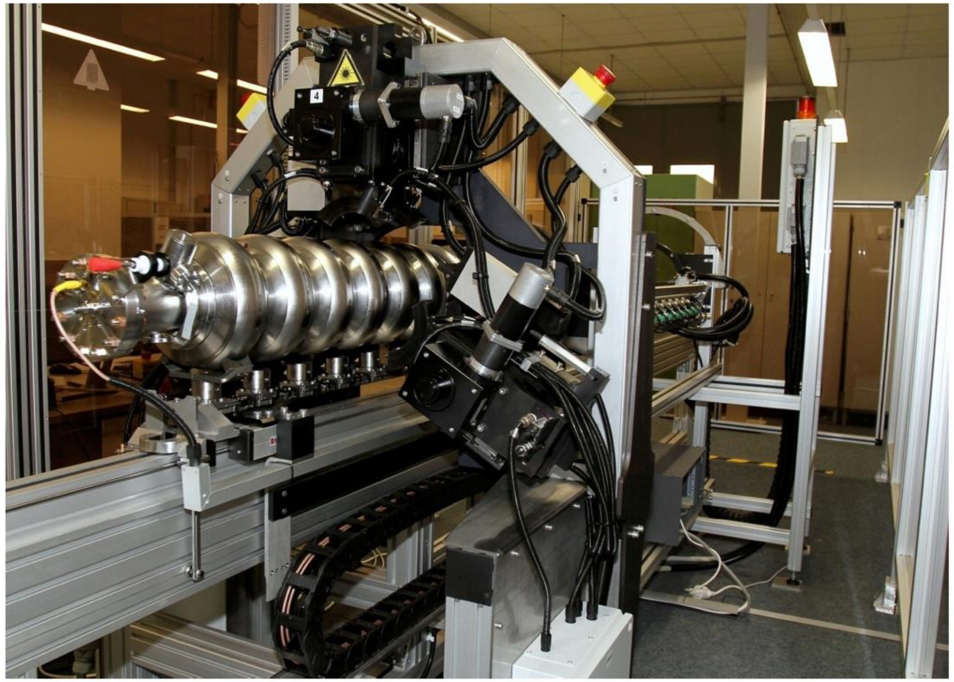
D.Reschke, A.Sulimov, D.Kostin

Major Infrastructures at EZ & RI

- 2 **EBW** (Electron Beam Welding) plants, equipped with cryo-pumps
- ISO 7 and ISO 4 **Clean Rooms** with cleaning and rinsing facility
- **UPW** (Ultra Pure Water - 18 MΩ·cm) production system (>3000 l/h)
- **HPR** (High Pressure Rinsing – 100 bar) apparatus

- **800 °C** and **120 °C ovens** operating with High Vacuum.
- Cavity Tuning Machine, **CTM**, provided by DESY
- **RF tests** set up (for **H**alf**C**ell, **D**umb**B**ells and **E**nd**G**roups), provided by DESY
- **US** (Ultra Sonic) cleaning baths
- Complete **chemical processing** plants (**EP**, **BCP** or both)
- Cavity internal **visual inspection** systems

Special Equipments installed in Industry



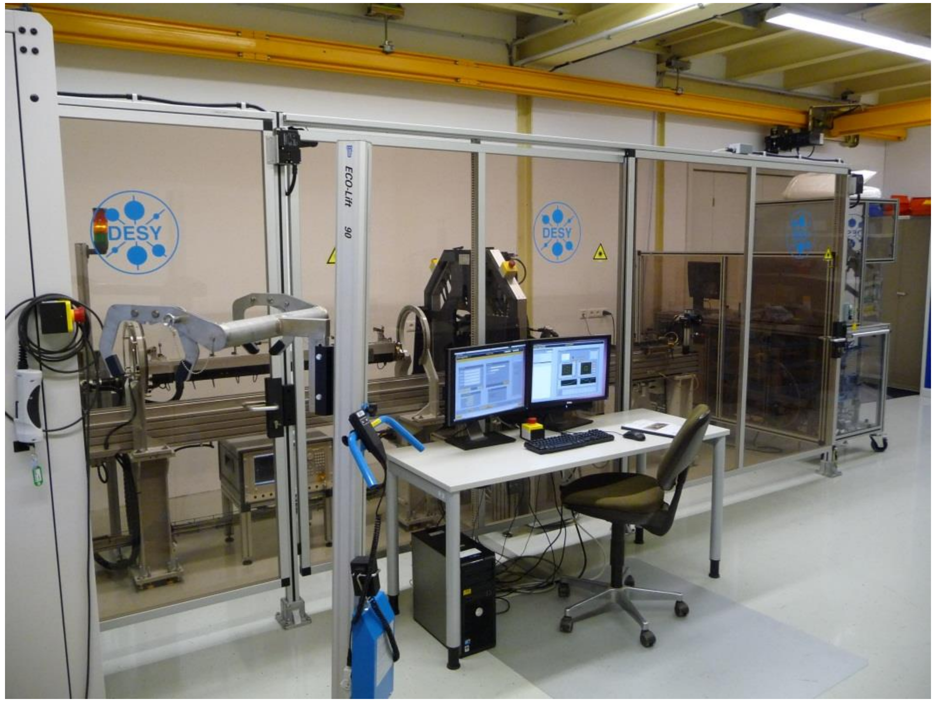
Machine for warm cavity tuning TM (tuning machine)

Equipment for RF measurement of half cells, dumb bells and end groups

Provided with CE certification according EU regulations

CTM cavity tuning machine and HAZEMEMA

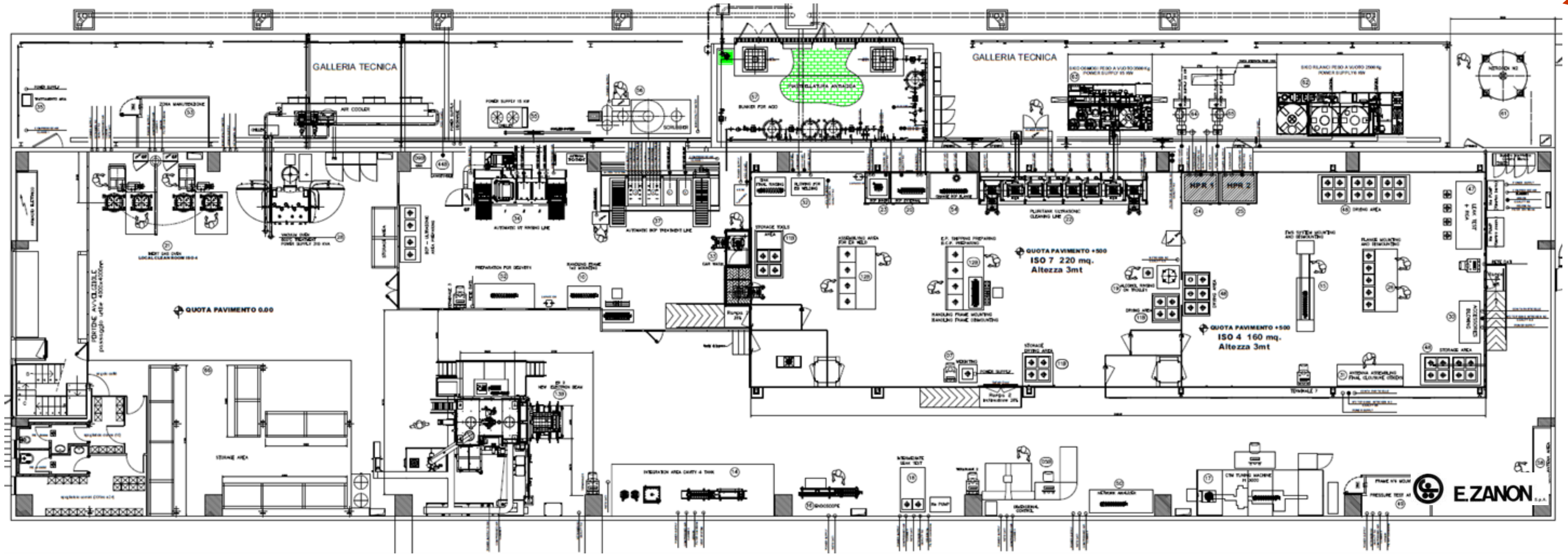
DESY developed, build and delivered to both companies a cavity tuning machine CTM and equipment for RF measurement on half cells, dumb-bells and end groups HAZEMEMA



CTM and HAZEMEMA installed at RI

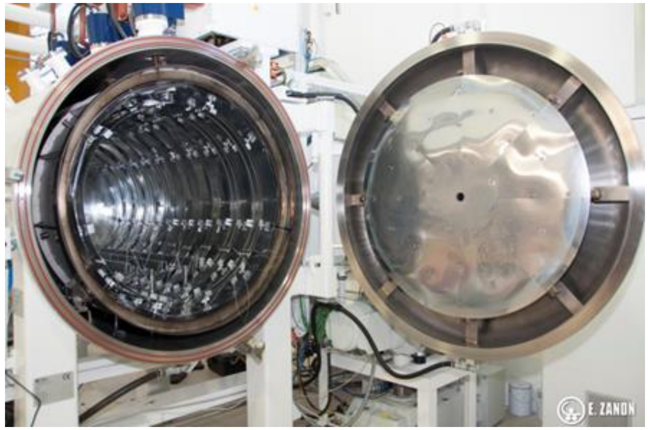
CTM in installation at EZ

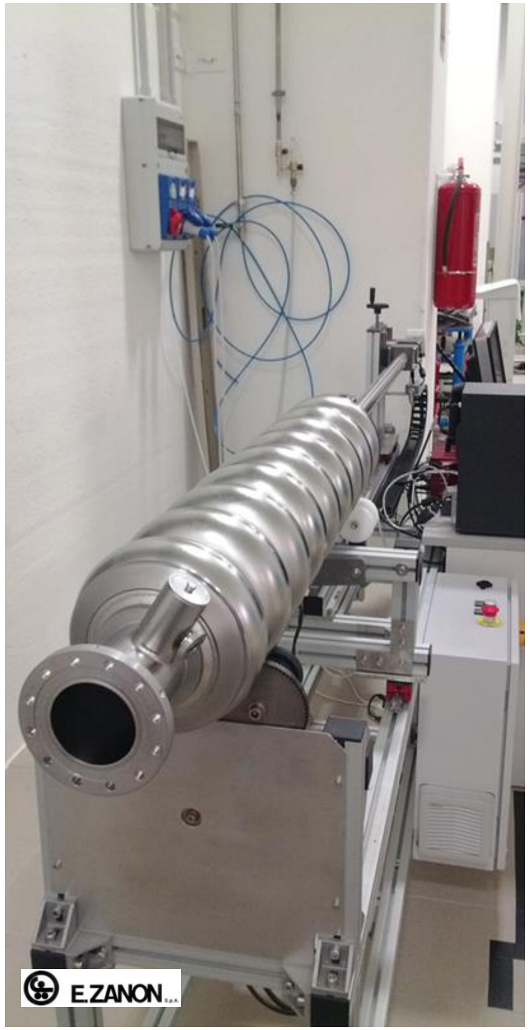
Cavity Infrastructure Layout at EZ



Building layout: clean rooms ISO10, ISO7, ISO4, US and BCP treatment, 120^{o}C baking, 800^{o}C oven, EBW, tuning machine etc.

Examples of EZ Infrastructure *(courtesy of EZ)*





New EBW machine

New oven for 800°C treatment

Borescope for optical inspection

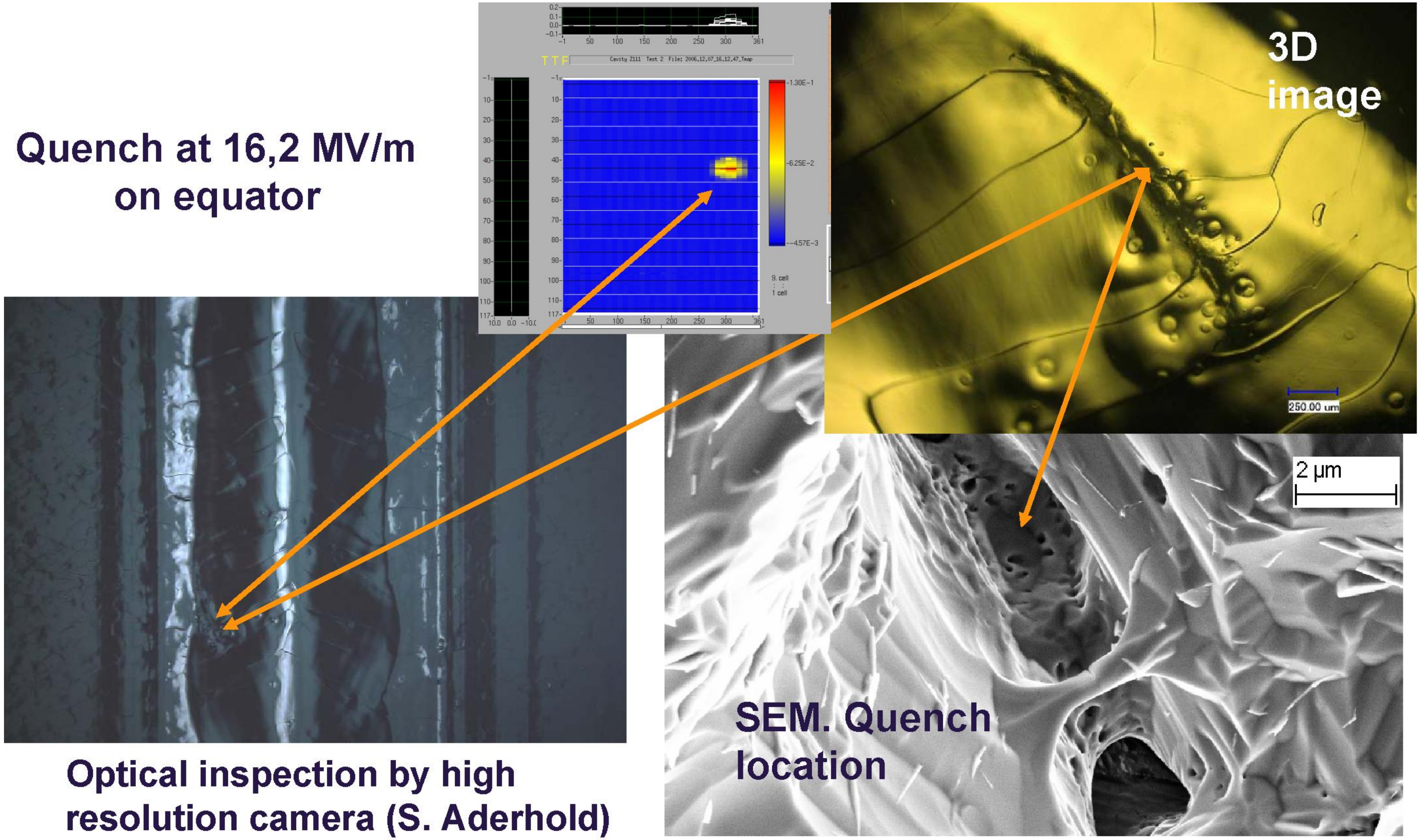
Examples of EZ Infrastructure *(courtesy of EZ)*

- **US cleaning and BCP in ISO 10 clean room**
- **ISO 4 installed in the new building**
- **The UPW (Ultra Pure Water) production system**

Deep Defect Analysis Capability @ Labs - 1

Topographical defects at the welding seams

Quench at 16,2 MV/m on equator

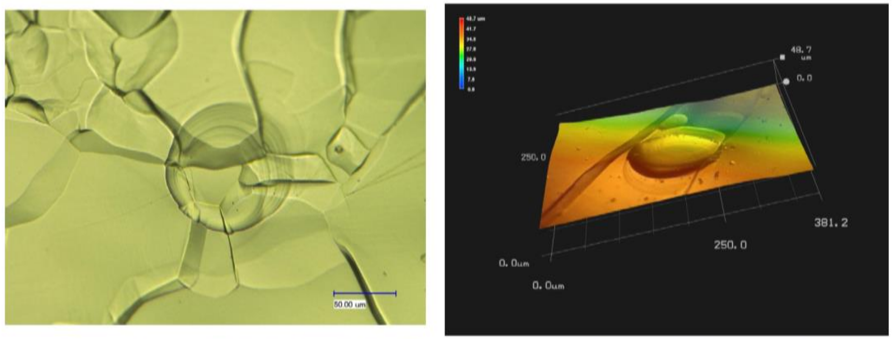


Optical inspection by high resolution camera (S. Aderhold)

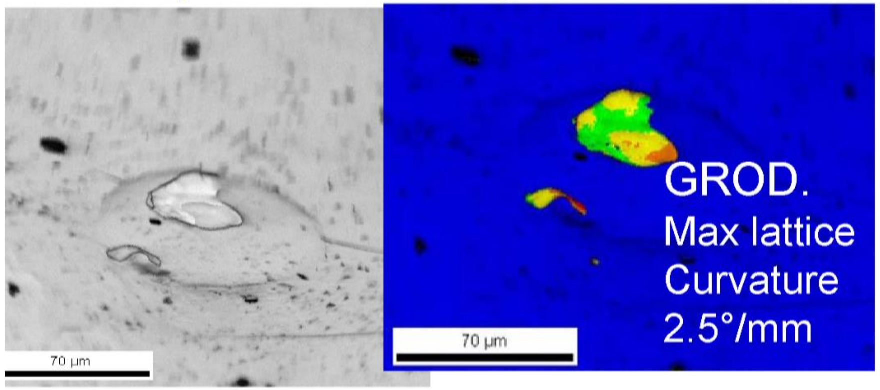
![IASF logo] ![INFN LASA logo]

Deep Defect Analysis Capability @ Labs - 2

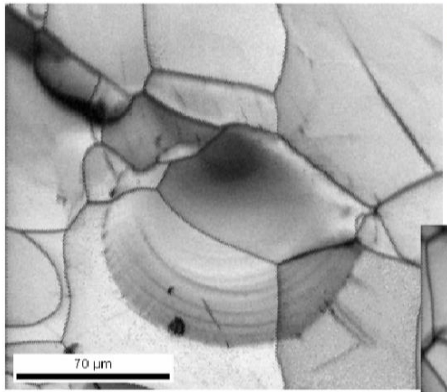
Etching pits: EBSD with strain maps via grain reference orientation deviation (GROD)



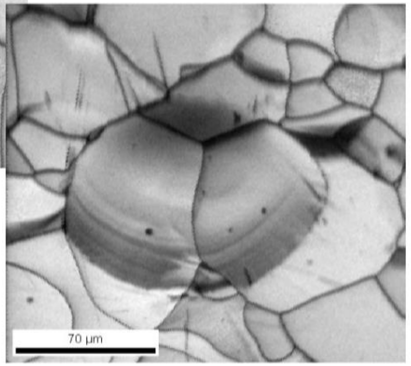
Cavity Z111: 3D Images of etching pits



Z111: Pit in heat affected zone HAZ of weld, enclosing region of strain, all within one grain (R. Croocs)



Pits away from the weld, with grain boundary triple junctions

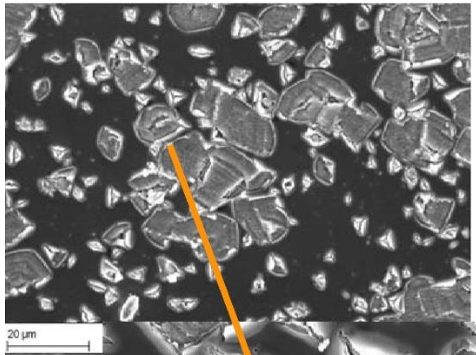


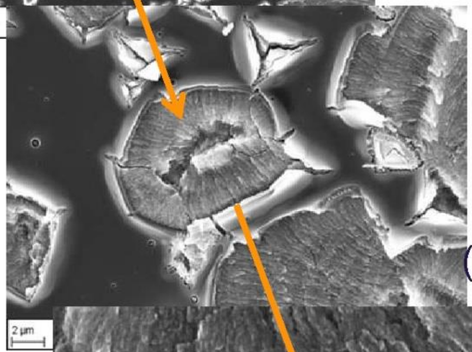
- **Pits don't seem to be related to grain orientation**
- **Pits in weld HAZ are near areas of remaining cold work (high dislocation density)**
- **Pits away from the weld, in fine grain area tend to be centered on grain boundary triple junctions**

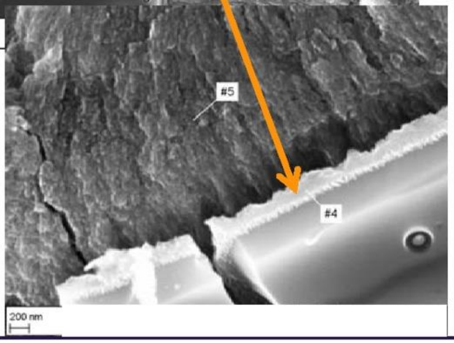
Deep Defect Analysis Capability @ Labs - 3

Dangerous surface defects generated by bad HPR (Hihg Pressure Water rinsing)

Auger spectrums indicates very high presence of oxygen.







S E M Images

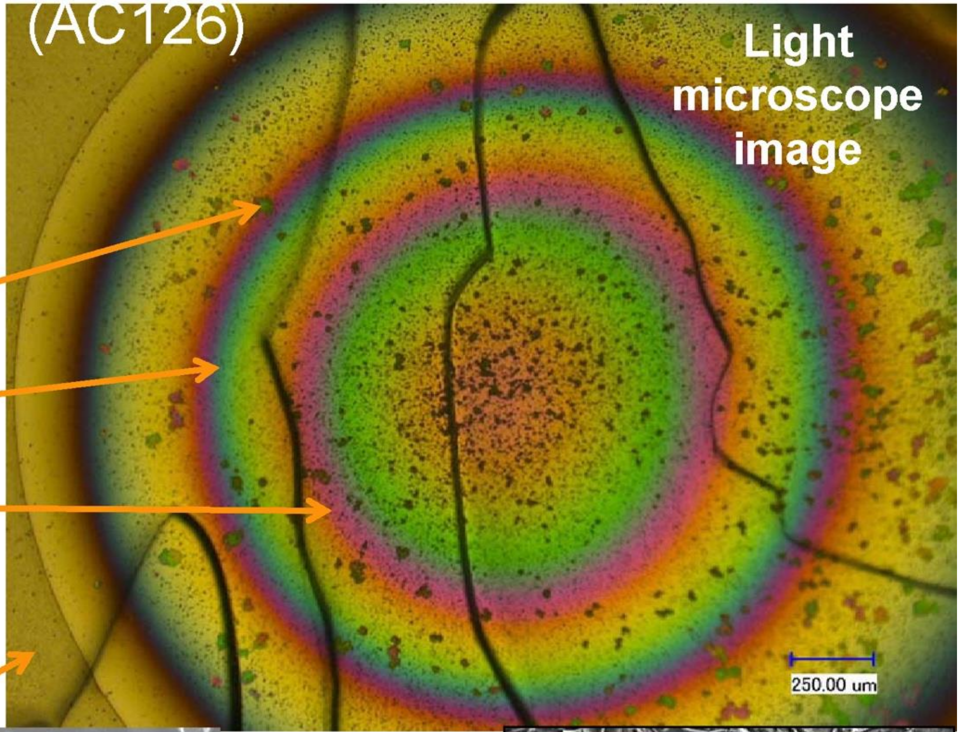
Oxide layer with thickness:

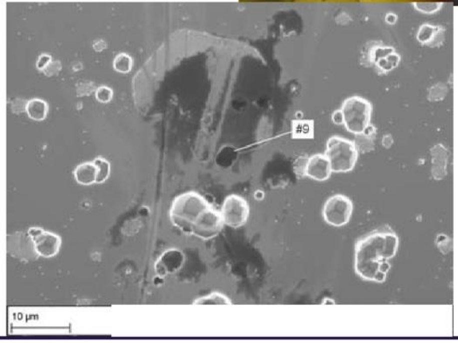
>114 nm (spot)

32.5 nm (blue)

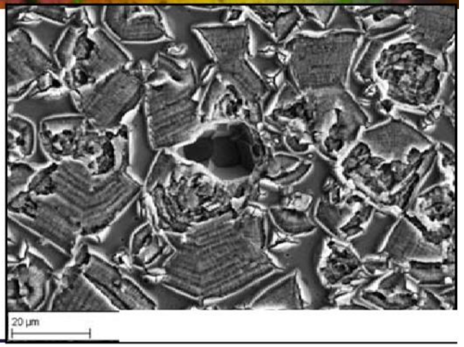
195 nm (red)

13 nm (outside rings)





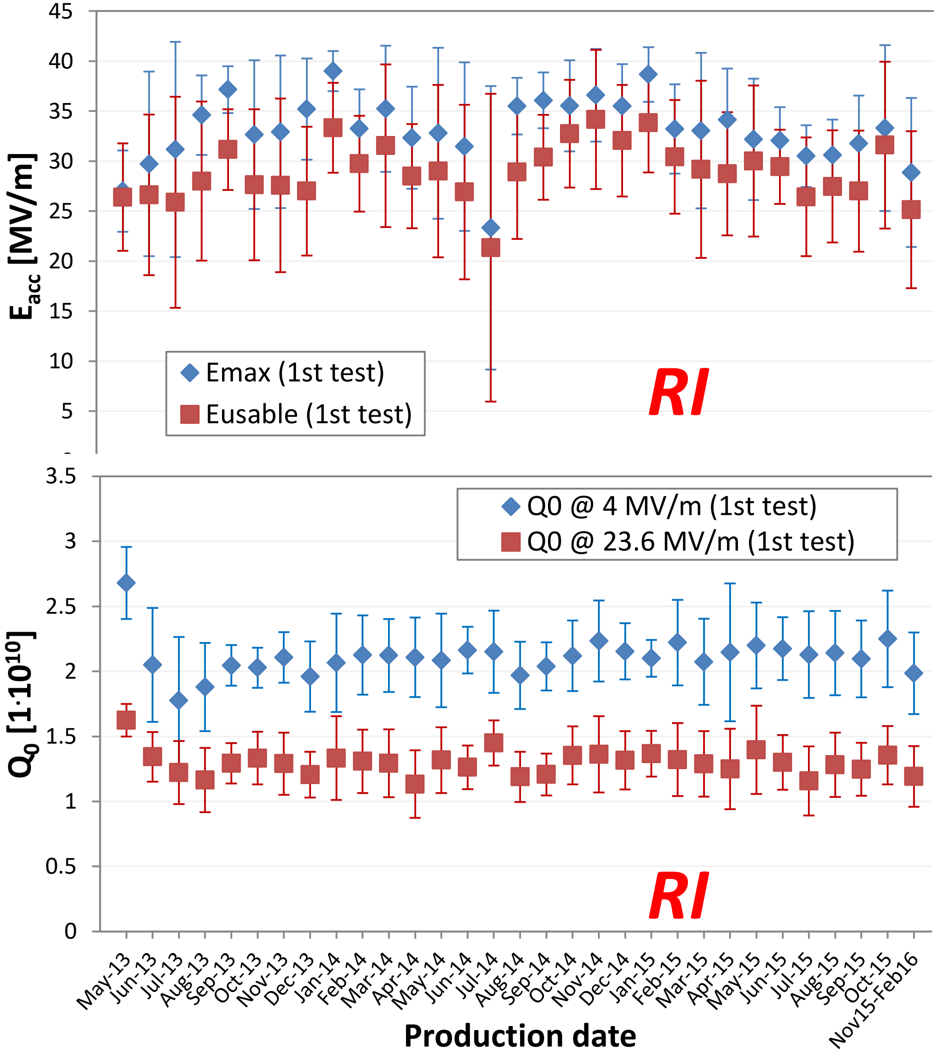
SEM image of the black spots EDAX indicates carbon



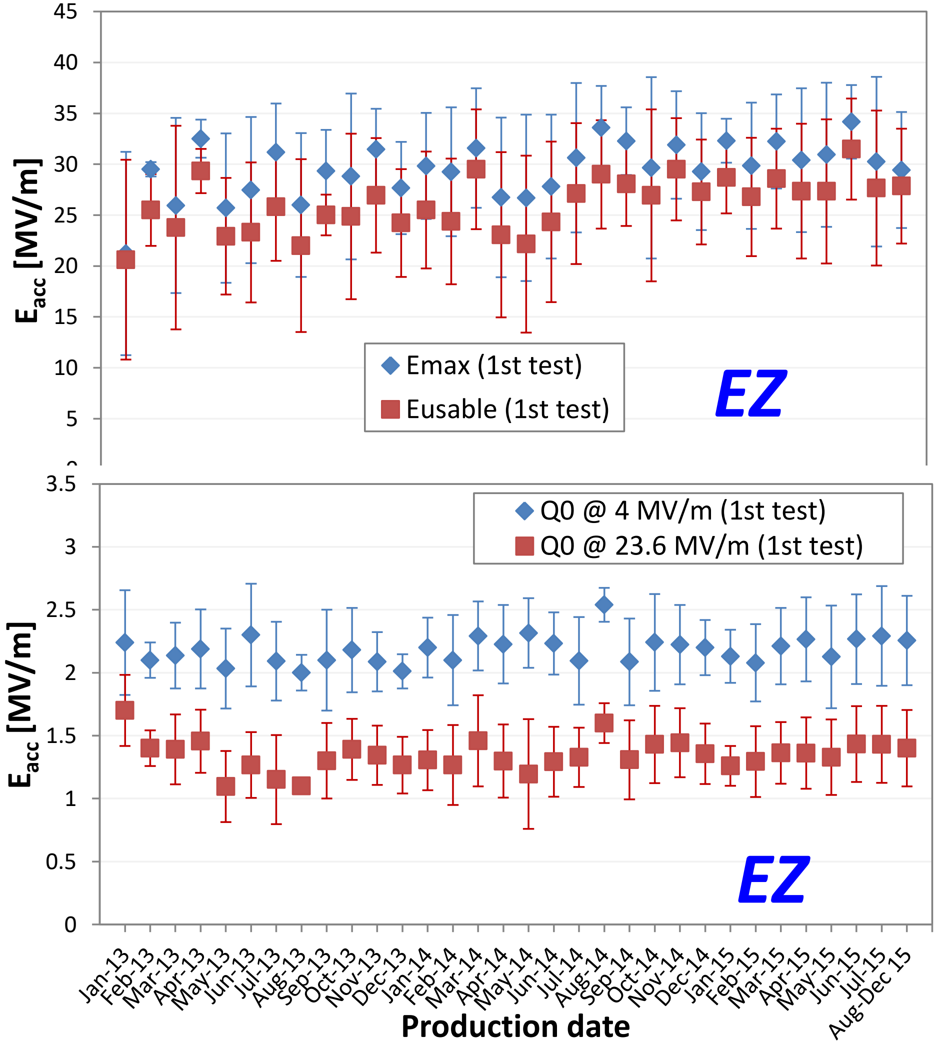
Contents

1.3 GHz E-XFEL cavities «as received»

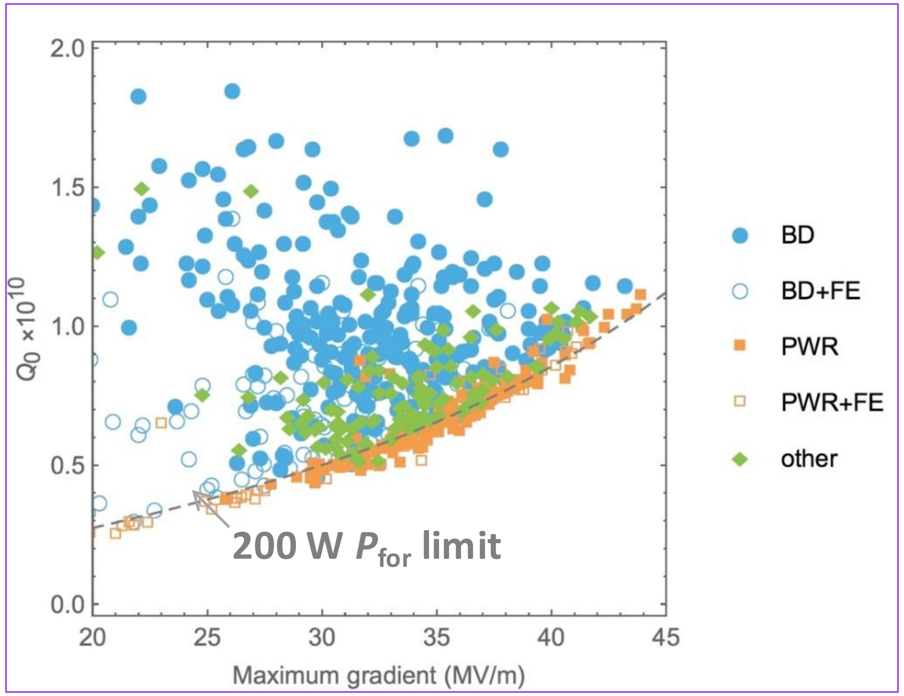
EP

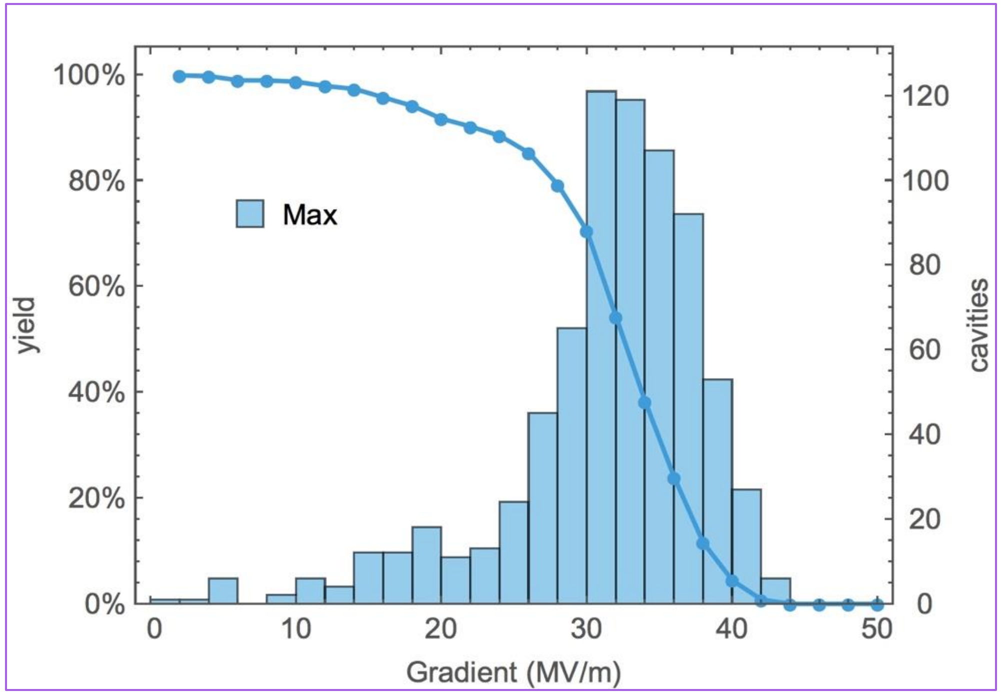


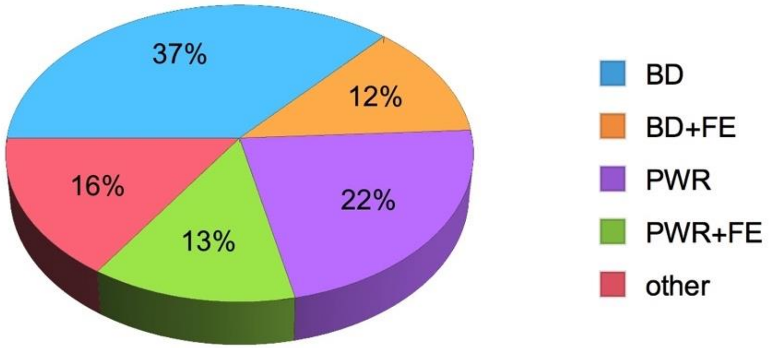
BCP



As Received Maximum Gradient







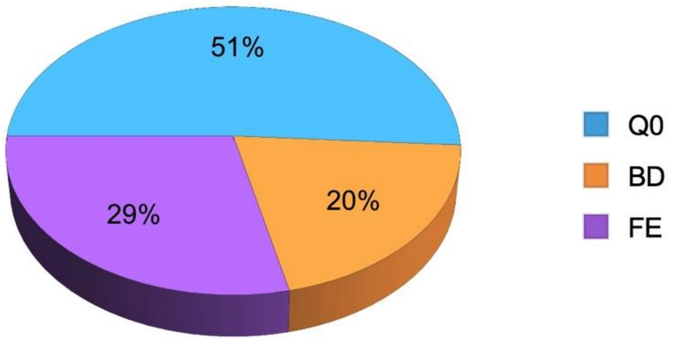
		Max
Average	MV/m	31.4
RMS	MV/m	6.8
Median (50%)	MV/m	32.5
Yield ≥20 MV/m		92%
Yield ≥26 MV/m		85%

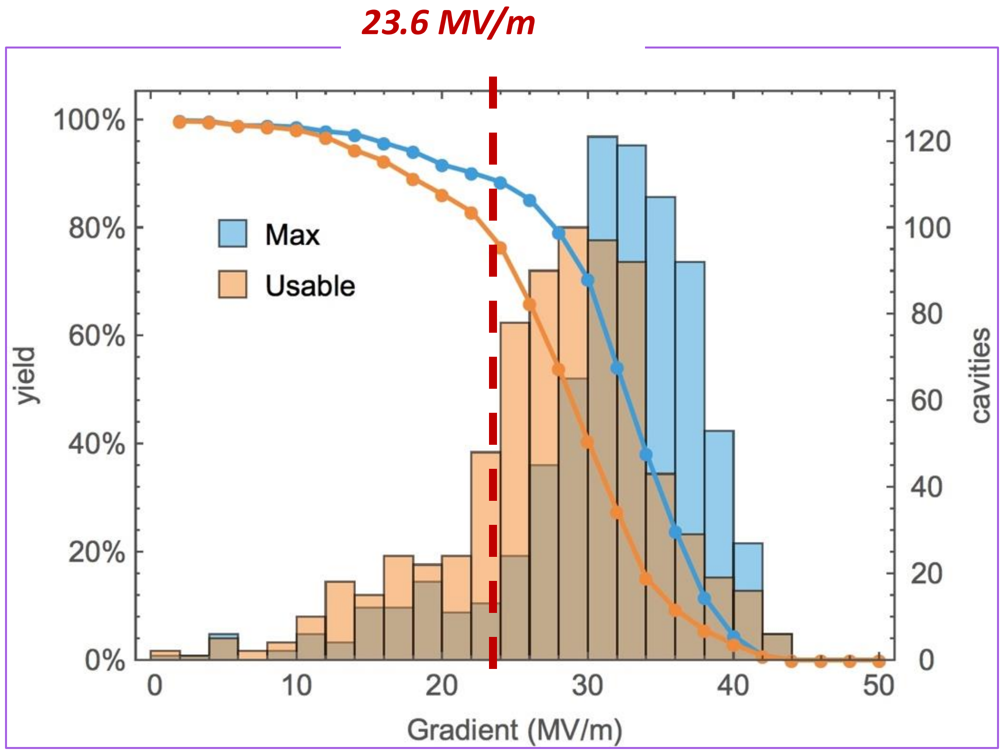
As Received Usable Gradien

Include operations spec

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

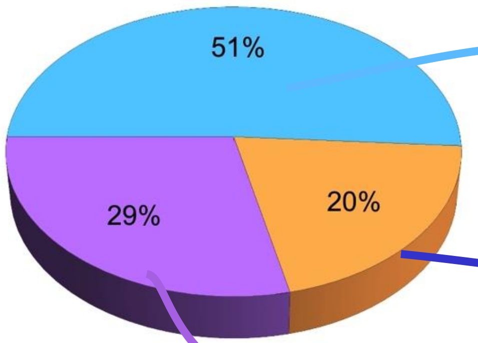
→ Usable Gradient

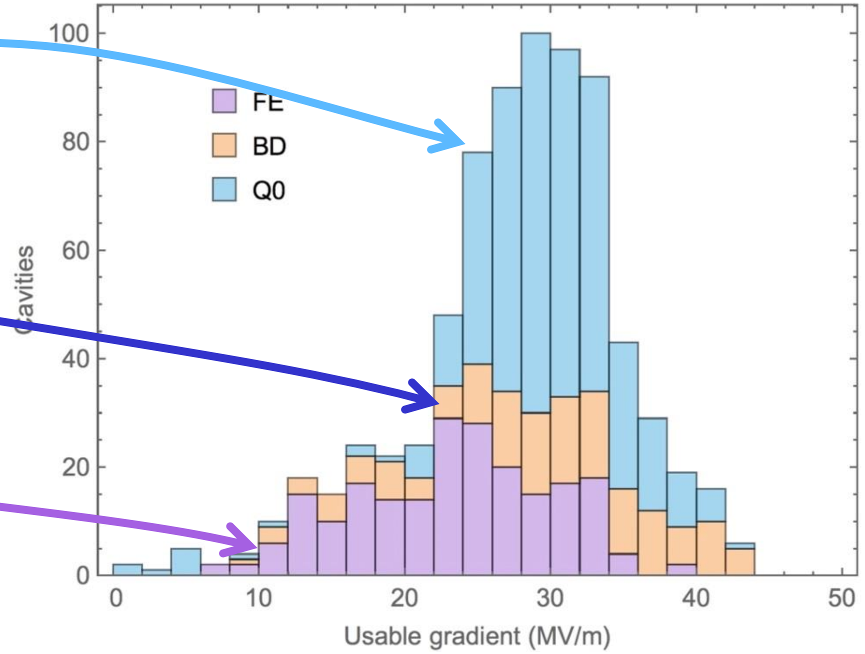




		Max	Usable
Average	MV/m	31.4	27.7
RMS	MV/m	6.8	7.2
Median (50%)	MV/m	32.5	28.7
Yield ≥20 MV/m		92%	86%
Yield ≥26 MV/m		85%	66%

As Received Usable Gradient





Include operations spec

- $Q_0 \geq 1\times10^{10}$
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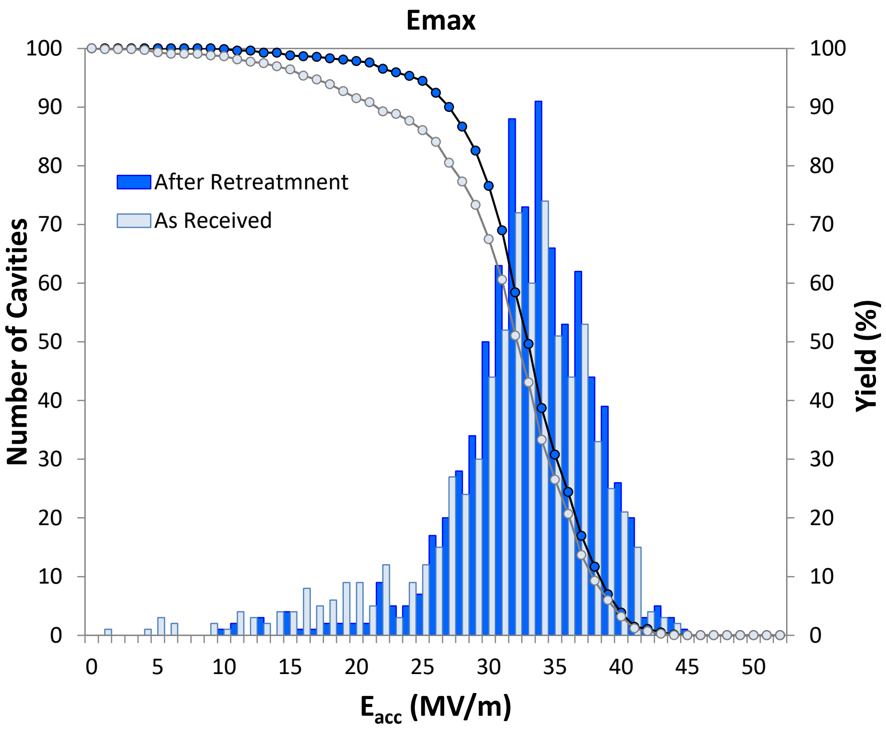
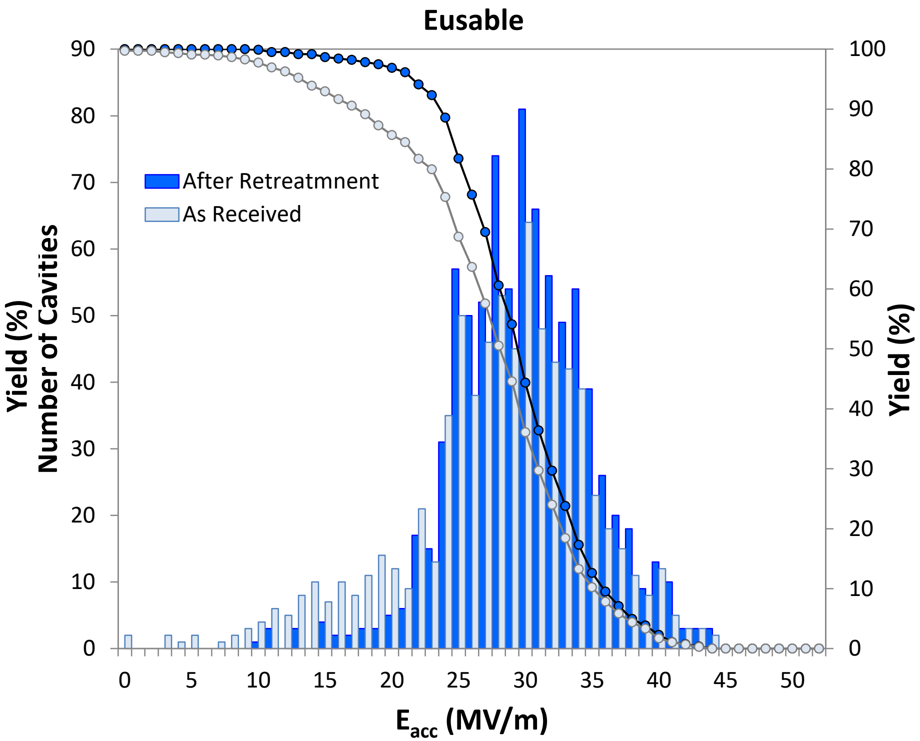
Yield ≥20 MV/m		92%	86%
Yield ≥26 MV/m		85%	66%

Final performance: Eacc

Total after 313 retreatments performed on 237 of the 831 cavities





Before:

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])

After:

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])

Before:

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])

After:

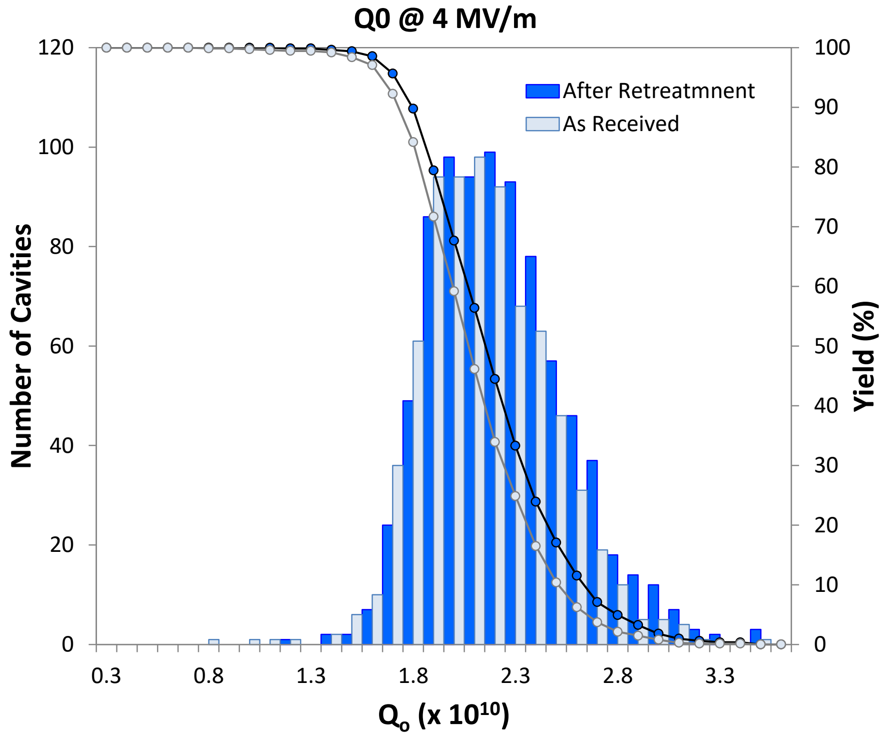
E usable 29.8 ± 5.1 [MV/m]

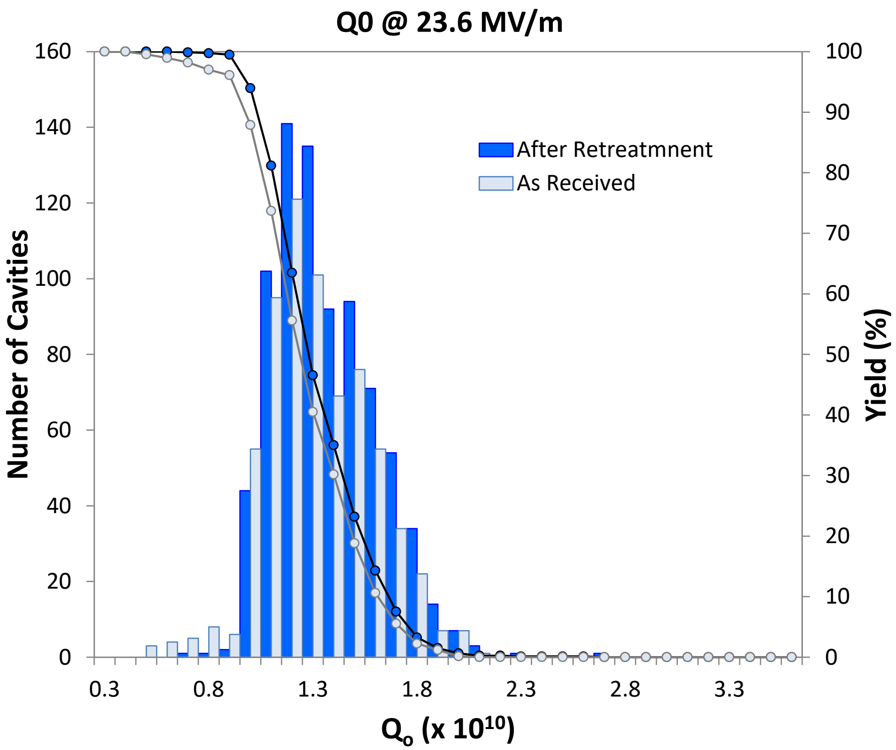
(RI): E usable 31.2 ± 5.2 [MV/m])

(EZ): E usable 28.6 ± 4.8 [MV/m])

Final performance: Q0

Total after 313 retreatments performed on 237 of the 831 cavities





Before :

Q0 @ 4 MV/m 2.15 ± 0.32 [$1 \cdot 10^{10}$]

(RI): Q0 @ 4 MV/m 2.11 ± 0.32 [$1 \cdot 10^{10}$])

(EZ): Q0 @ 4 MV/m 2.18 ± 0.32 [$1 \cdot 10^{10}$])

After:

Q0 @ 4 MV/m 2.23 ± 0.34 [$1 \cdot 10^{10}$]

(RI): Q0 @ 4 MV/m 2.21 ± 0.34 [$1 \cdot 10^{10}$])

(EZ): Q0 @ 4 MV/m 2.26 ± 0.33 [$1 \cdot 10^{10}$])

Before:

Q0 @ 23.6 MV/m 1.31 ± 0.26 [$1 \cdot 10^{10}$]

(RI): Q0 @ 23.6 MV/m 1.29 ± 0.24 [$1 \cdot 10^{10}$])

(EZ): Q0 @ 23.6 MV/m 1.34 ± 0.28 [$1 \cdot 10^{10}$])

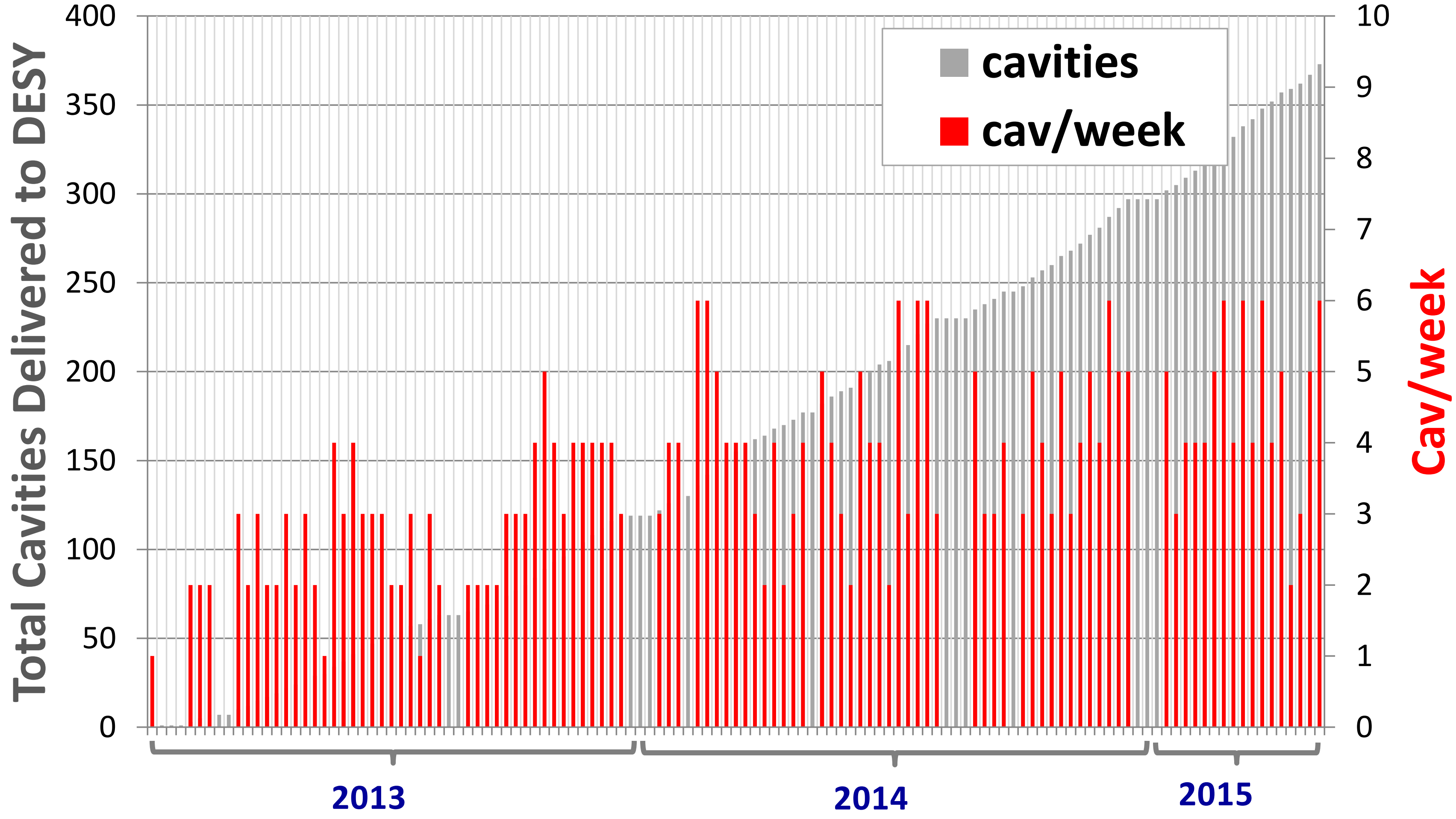
After:

Q0 @ 23.6 MV/m 1.37 ± 0.25 [$1 \cdot 10^{10}$]

(RI): Q0 @ 23.6 MV/m 1.34 ± 0.22 [$1 \cdot 10^{10}$])

(EZ): Q0 @ 23.6 MV/m 1.41 ± 0.26 [$1 \cdot 10^{10}$])

E-XFEL experience on cavity production rate



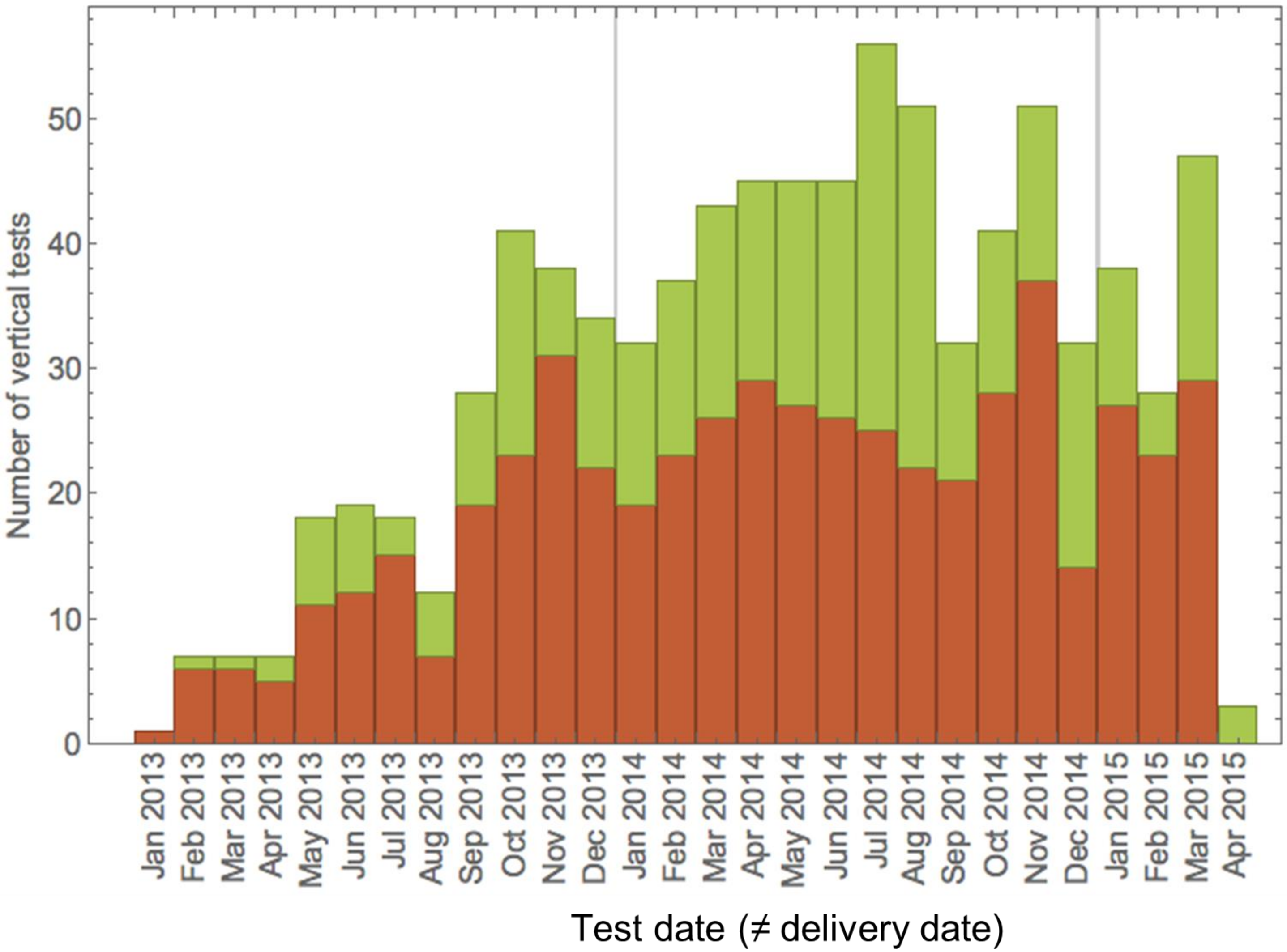
EZ cavity production udated on May 6th, 2015

Vertical TEST Infrastructure at DESY

- Multiple vertical tests started in Feb 2013 (IFJ-Pan & DESY)
- 2 independent cryostats and RF stations for six 4-cavity inserts
- Parallel commissioning of inserts + vertical tests on series cavities
- New software for vertical tests

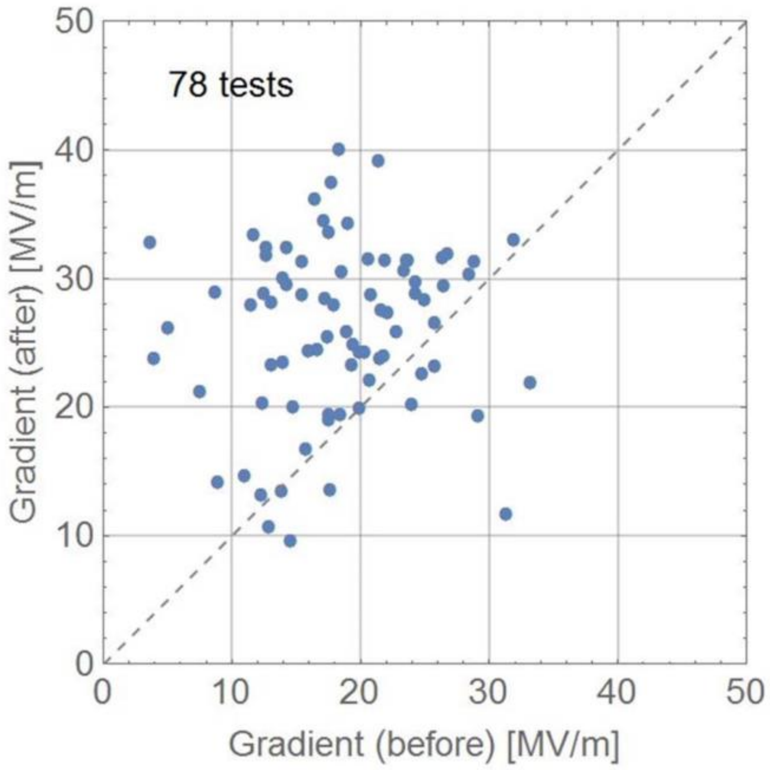
no Second Sound, no T-Mapping at AMTF

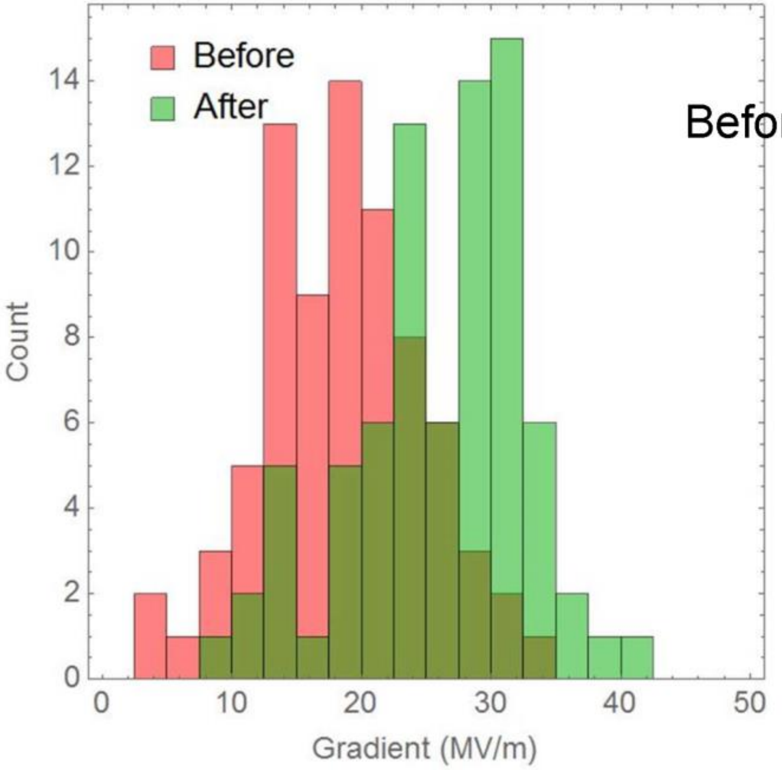
XFEL cavities: verticat test rate



Average:
~ 40 tests / month

Effect of HPR after transportation: E_{acc}





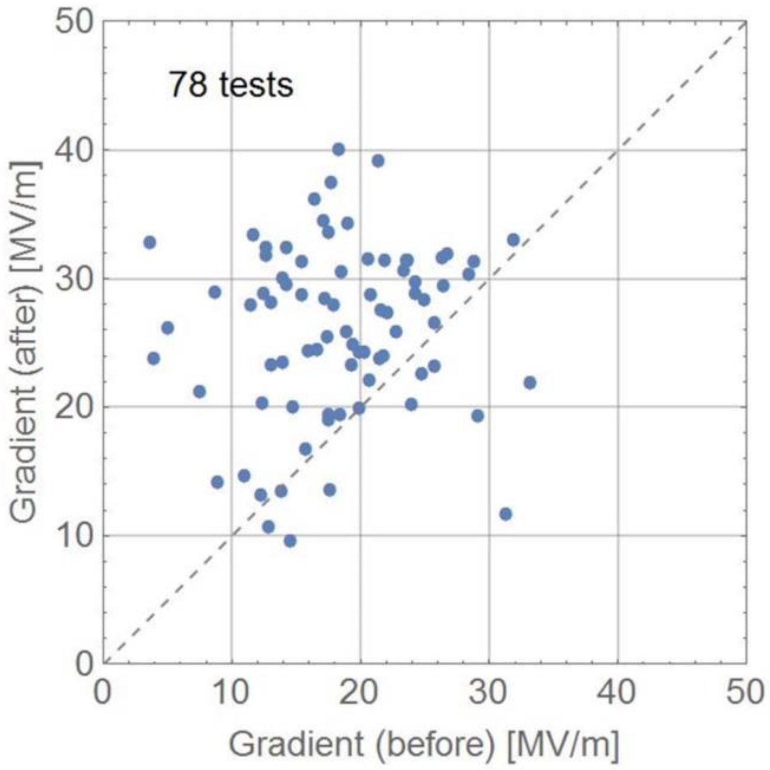
Before = as received

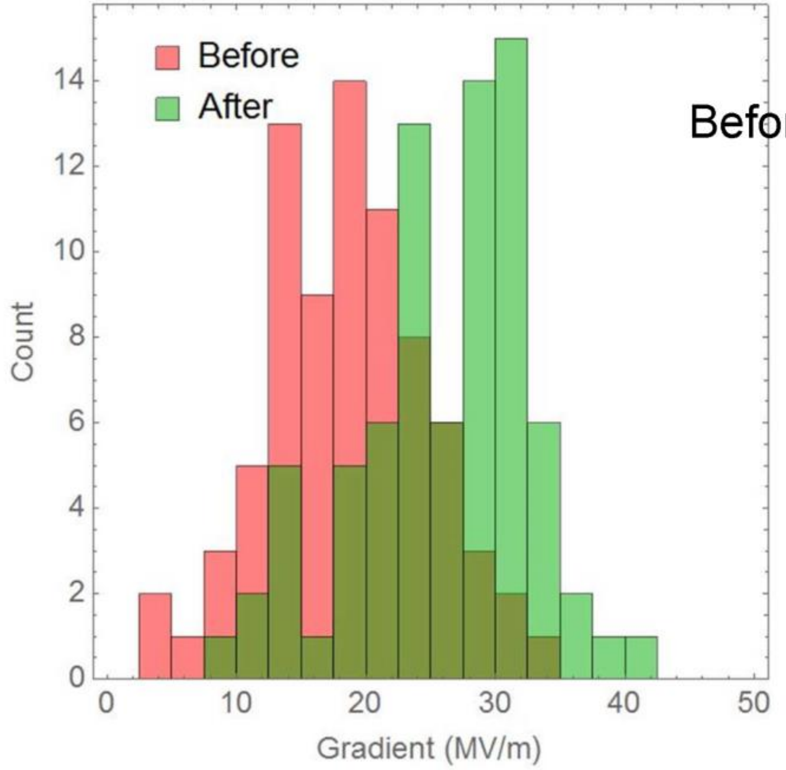
retreatment, low Q	4
retreatment, quench	6
retreatment, FE	59
retreatment, other	7
retreatment, leak	2

	Before	After
Tests	78	78
G_{AVG} (MV/m)	18.5	26.1
G_{RMS} (MV/m)	6.3	6.7
yield @ 20MV/m	40%	82%
yield @ 26MV/m	12%	54%
yield @ 28MV/m	8%	47%

Total:
~150 retreatments

Effect of HPR after transportation: Q_0





Before = as received

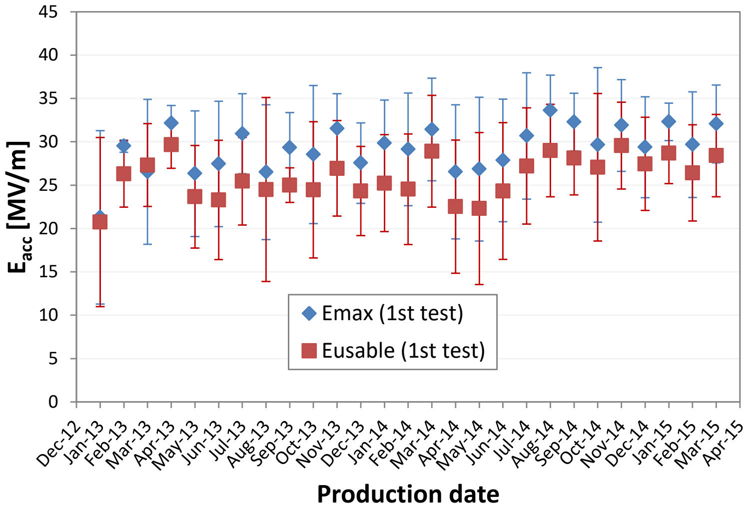
retreatment, low Q	4
retreatment, quench	6
retreatment, FE	59
retreatment, other	7
retreatment, leak	2

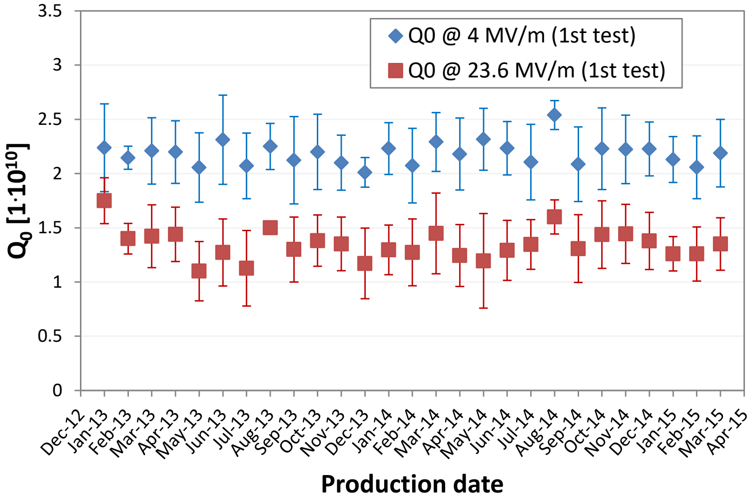
	Before	After
Tests	78	78
G_{AVG} (MV/m)	18.5	26.1
G_{RMS} (MV/m)	6.3	6.7
yield @ 20MV/m	40%	82%
yield @ 26MV/m	12%	54%
yield @ 28MV/m	8%	47%

Total:
~150 retreatments

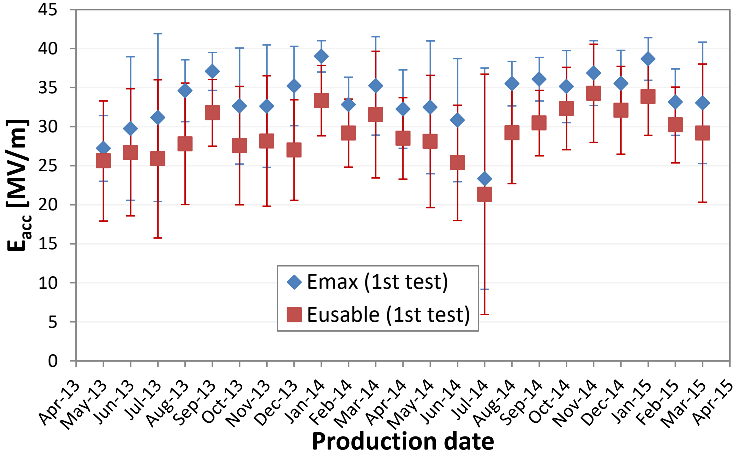
EP vs BCP: average E_{acc} and Q_0 /mounth

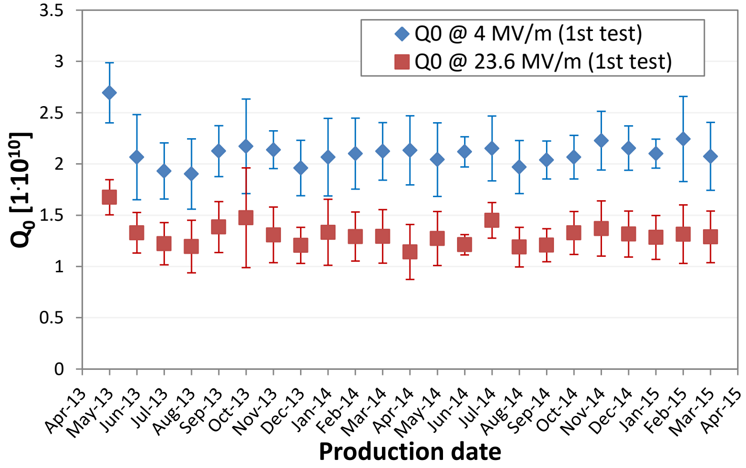
31 April 2015





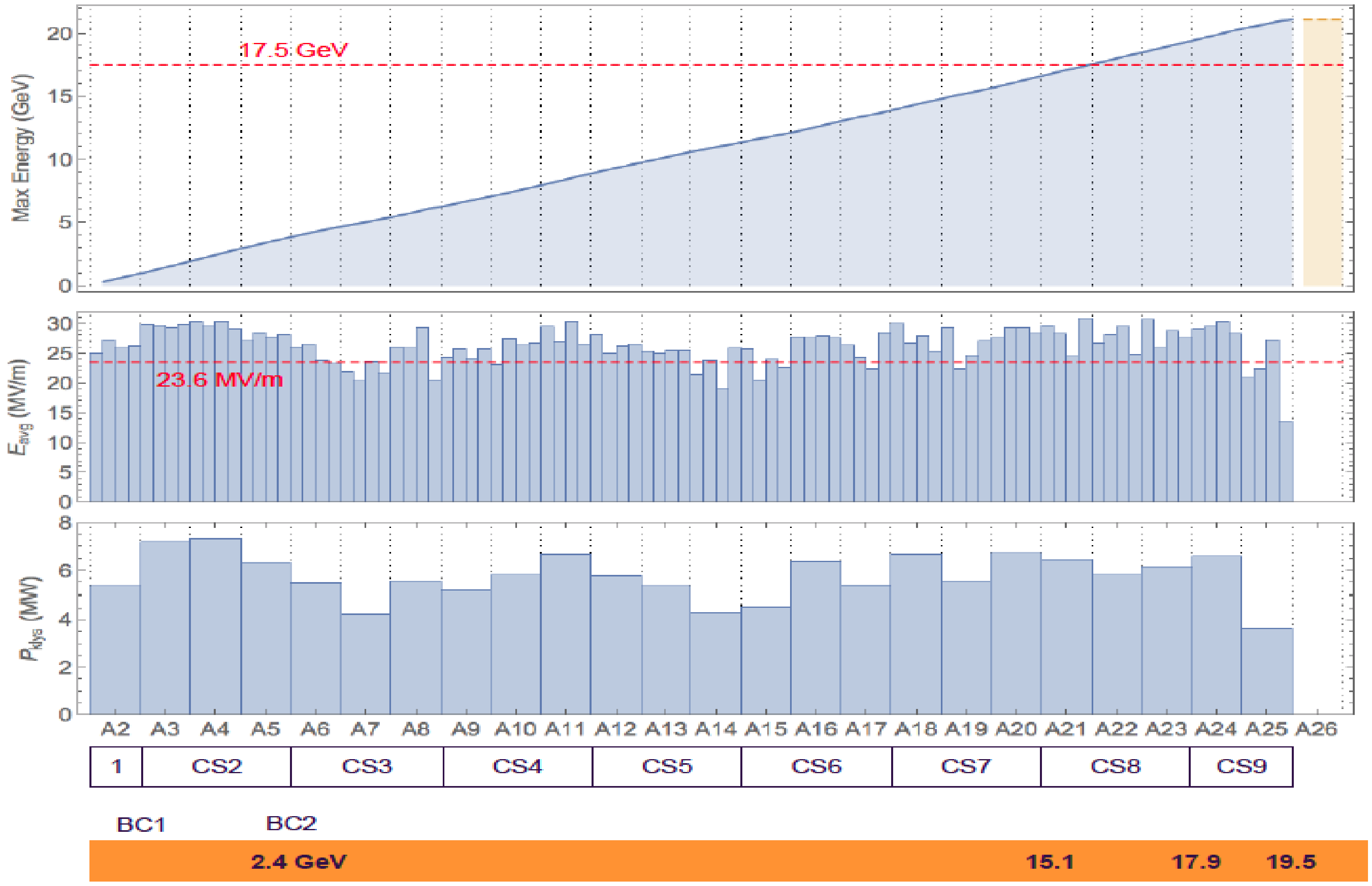
Final BCP





Final EP

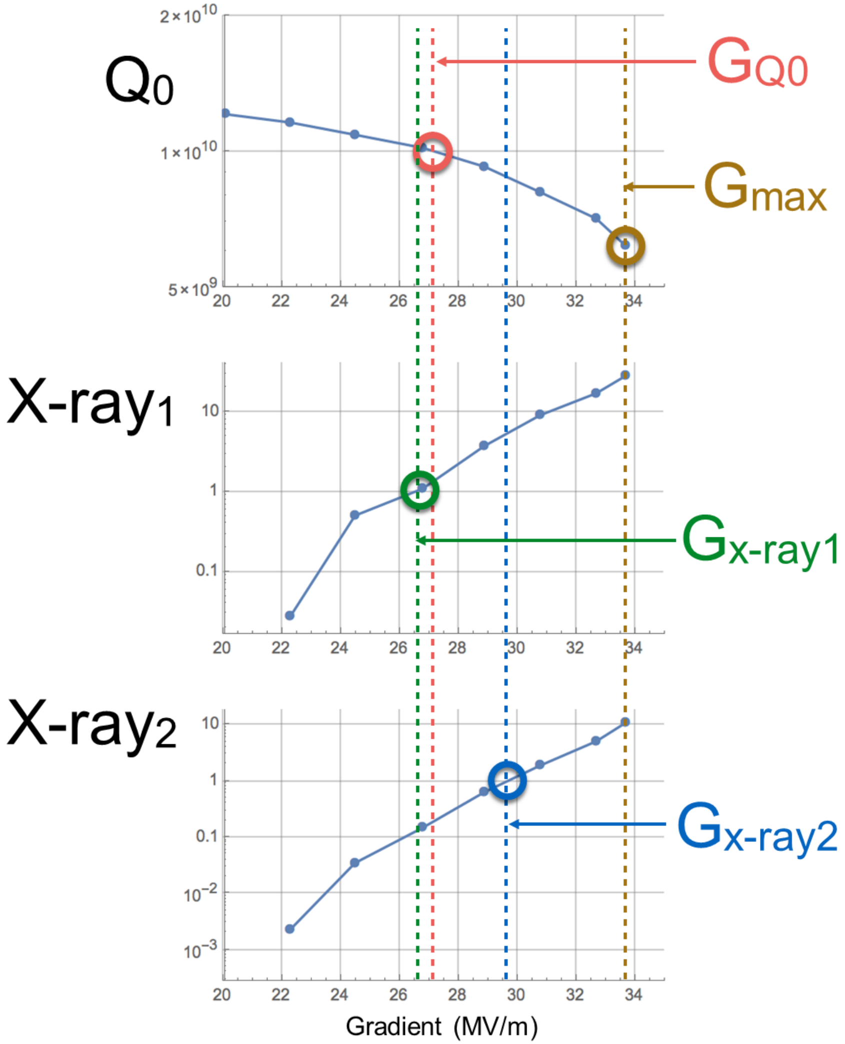
E-XFEL: Usable Installed Voltage



XFEL definition of usable gradient

- Minimum of the following gradient values:
  - MAX (i.e. quench)
  - $Q_0 = 10^{10}$
  - X-ray 1 (top) threshold
  - X-ray 2 (bottom) threshold

- In this example, usable gradient is limited by FE (X-ray$_1$) to ~27 MV/m
- max gradient is ~34 MV/m



Some consideration on the series production

Industry, once trained, **is doing as well as the lab** behind
Results obtained are **very close to** those available **more than 13 years ago,** the time of the ITRP

- Results depend on the technology applied
- The complete cycle in Industry improves the yield, but not dramatically

The possibility of a **second treatment is still mandatory** to improve the yield

- HPR is usually sufficient, flash BCP can be required, EP is excluded (HT installed)
- Second treatment is improving the yield, both for high field and field emission

Reference for CW after LCLS II

After XFEL**, EZ** & **RI** produced **all the 1.3 GHz cavities** for **LCLS II**, **including** final treatment and **Nitrogen doping**

All the cryomodules, modified for CW, are now produced **in China by Wuxi,** originally with **IHEP** supervision

DOE sbuscribed the high nominal value for the cavity Qo (as promissed by the succesfull application of the nitrogen doping) but **doubled the cryoplant**: **just in case**

Costing of XFEL was succesfully **based on industrial studies** performed by experienced companies

New large Projects should consider a very similar approach

Cavity packadge, criomodule and ancillaries are going together

Thank you for your attention