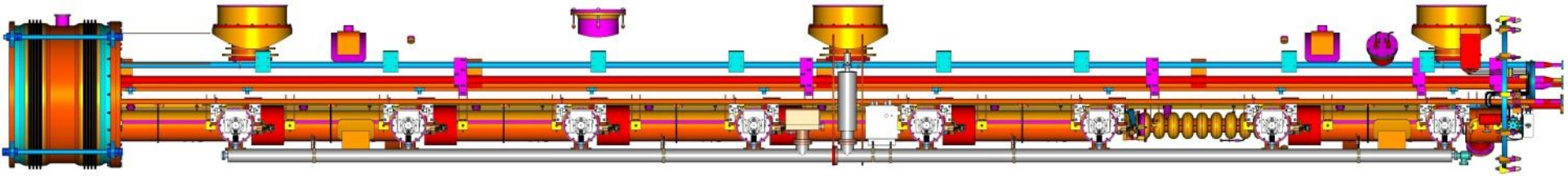
Assembly of XFEL Cryomodules: Lessons and Results

S. Berry, CEA-Saclay, Irfu/SACM

Outline



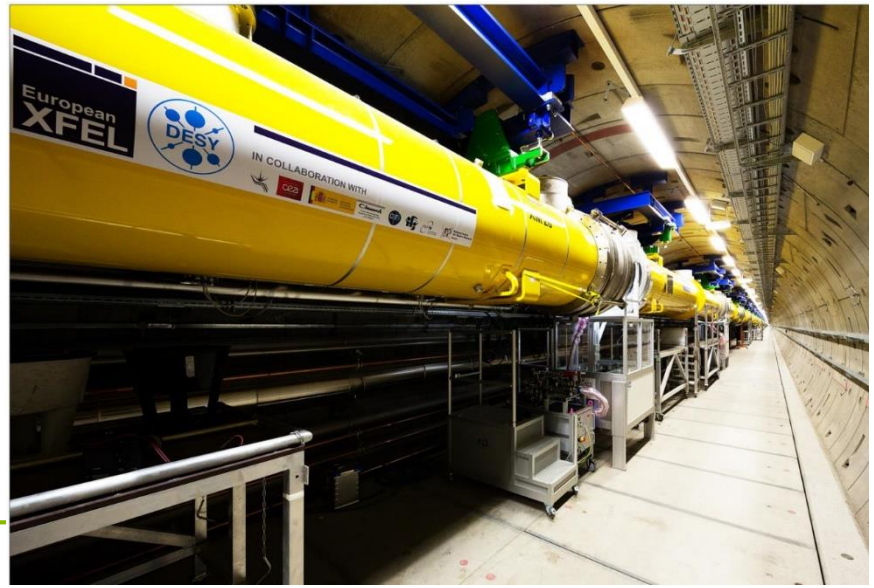
Cryomodule production

- Delivery and throughput
- Quality control

Module performance vs. Clean Room procedures

Module repair activities

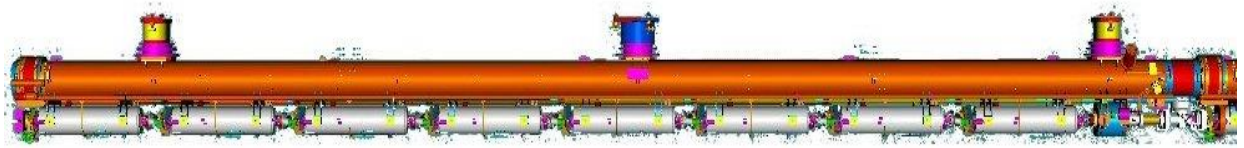
Conclusions



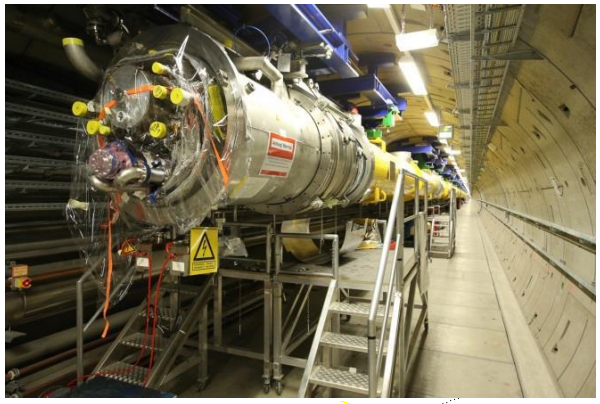
E-XFEL Cold Linac 17.5 GeV

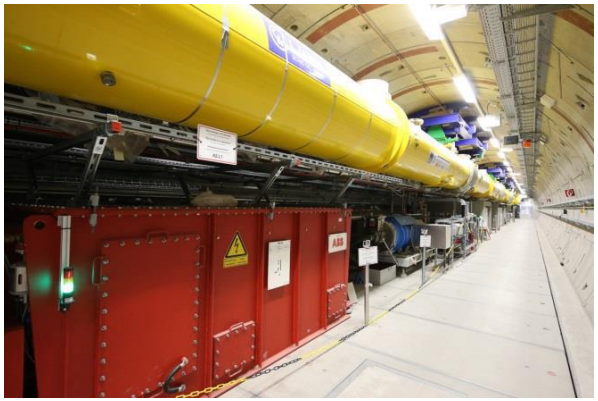
XFEL
X-Ray Free-Electron Laser

1 + 100 accelerator modules

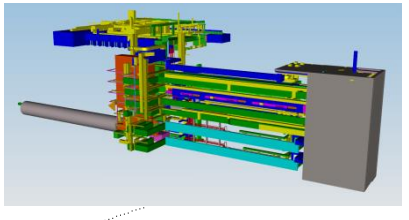


808 accelerating cavities
1.3 GHz / 23.6 MV/m / 10^{10}





25 RF stations
5.2 MW each



Cryomodule Production

CEA deliverable to European XFEL:

assembly of 103 accelerator modules

on the Saclay site and with CEA* infrastructure

* nine pumping systems (with mass-spectrometer) and one laser-tracker from DESY

* two tuner control racks from INFN

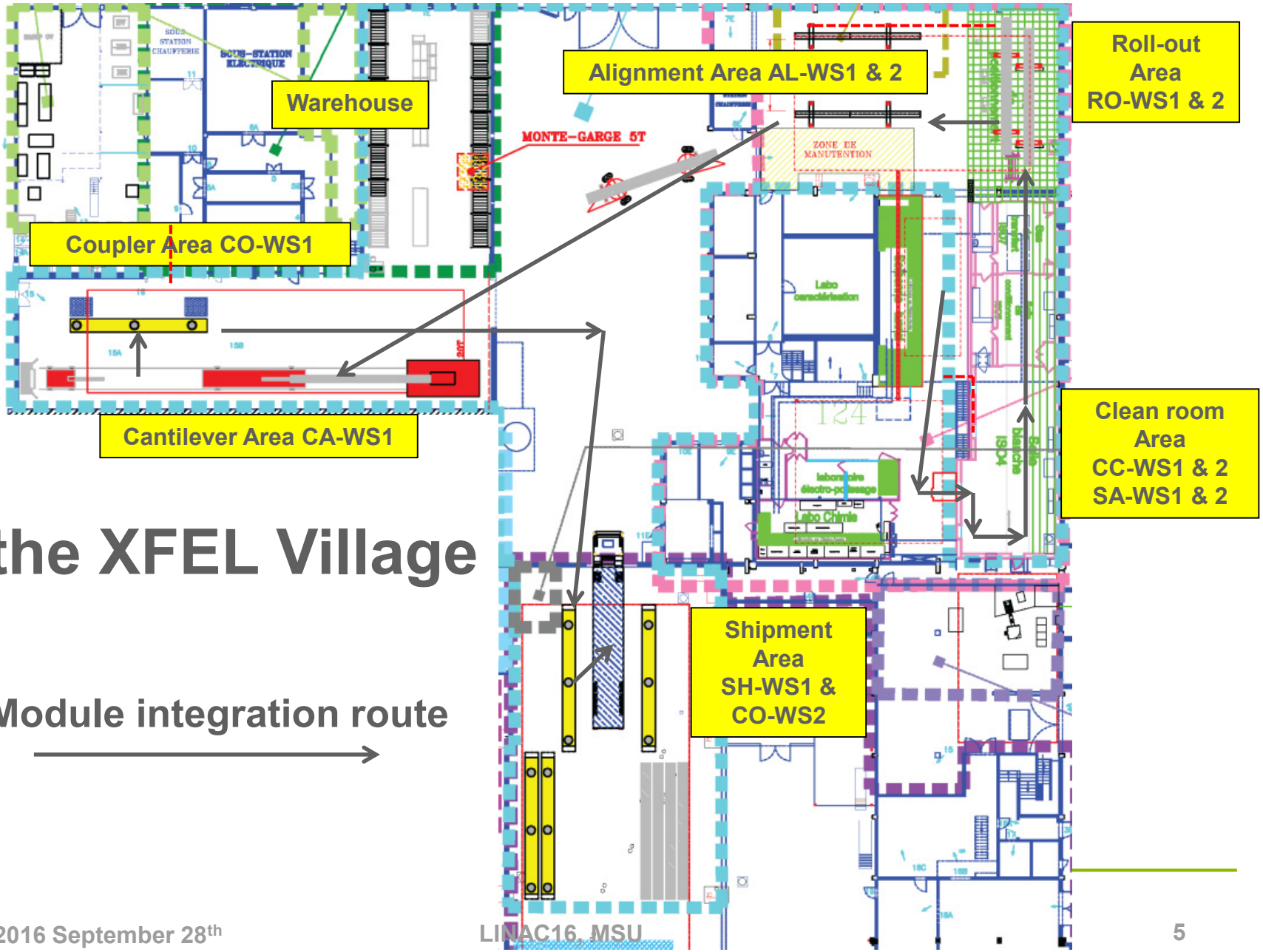
↓

Workforce by an industrial contractor Alsyom:

→ **Quantity production goal: 1 module / week**

→ **Quality performance goal: E_{acc} > 23,6 MV/m**

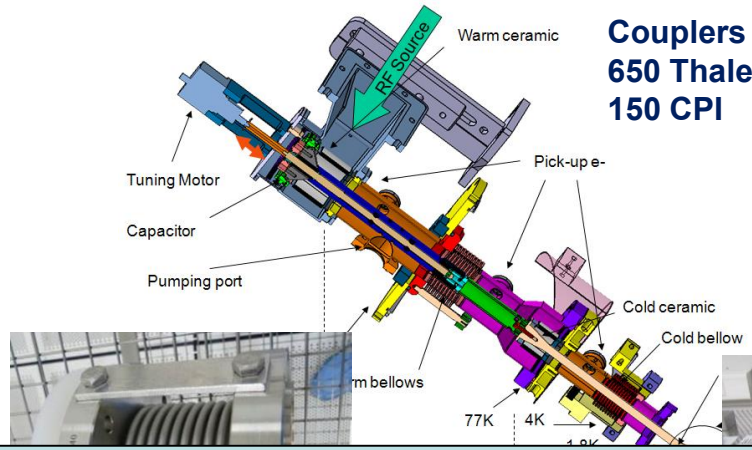
Assembly Hall : Workstations



the XFEL Village

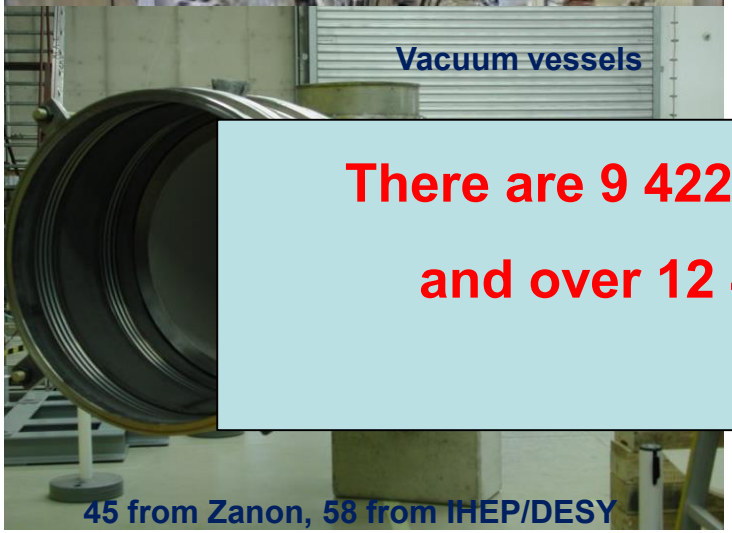
Module integration route →

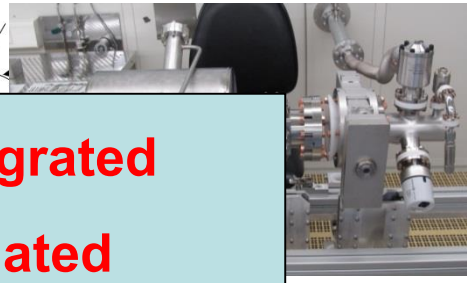
Component Industrialization / Handover



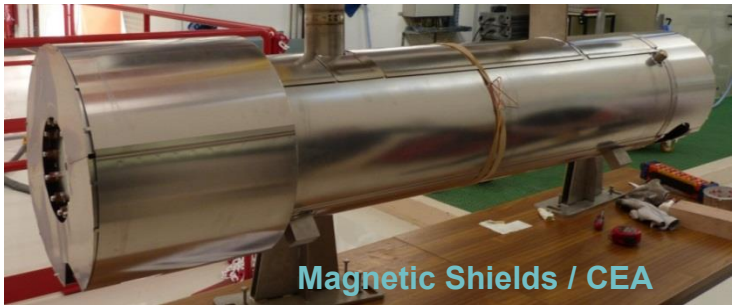
Couplers / IN2P3
650 Thales-RI
150 CPI

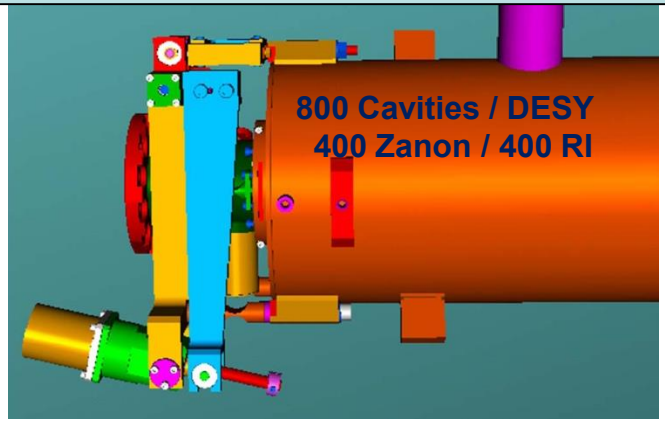
Quadrupole-BPM / DESY
103 Magnets / Ciemat
BPM / 72 DESY – 31 CEA
206 Gate Valves / DESY



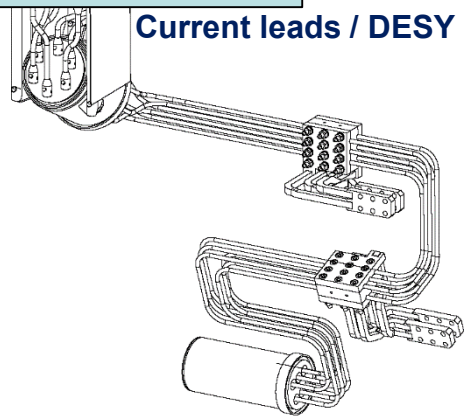


There are 9 422 individual components integrated and over 12 400 individual parts manipulated per cryomodule





Current leads / DESY



Cryomodule Delivery

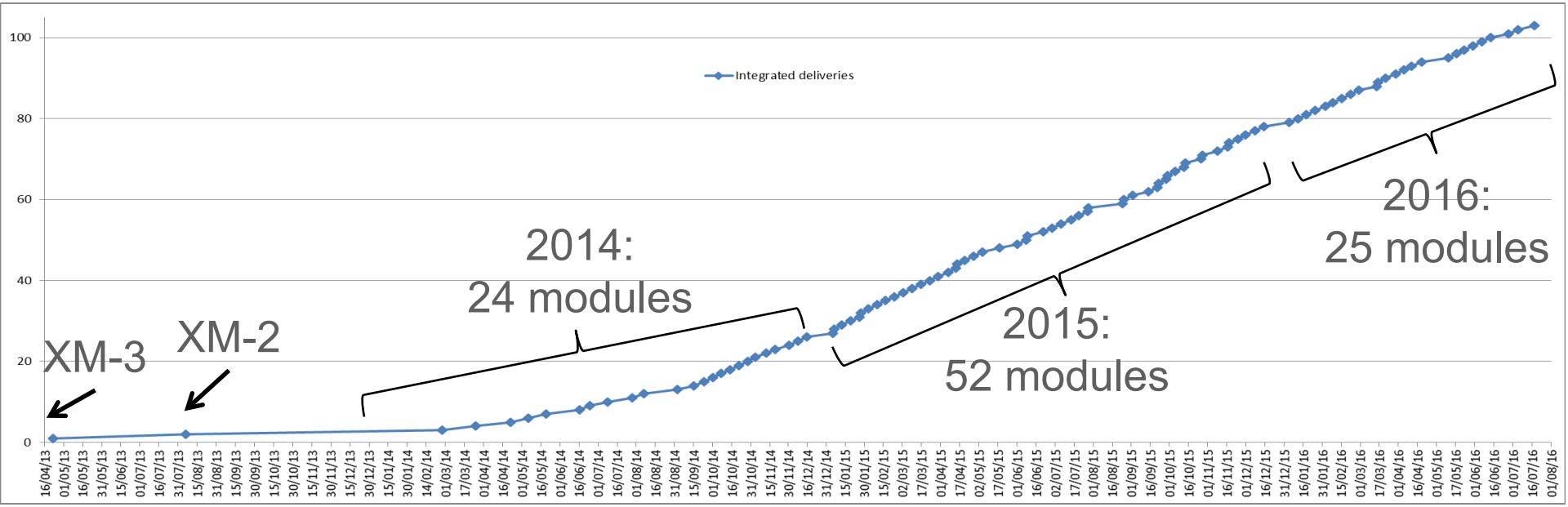


Figure: *delivery of cryomodules, from XM-3 to XM100*

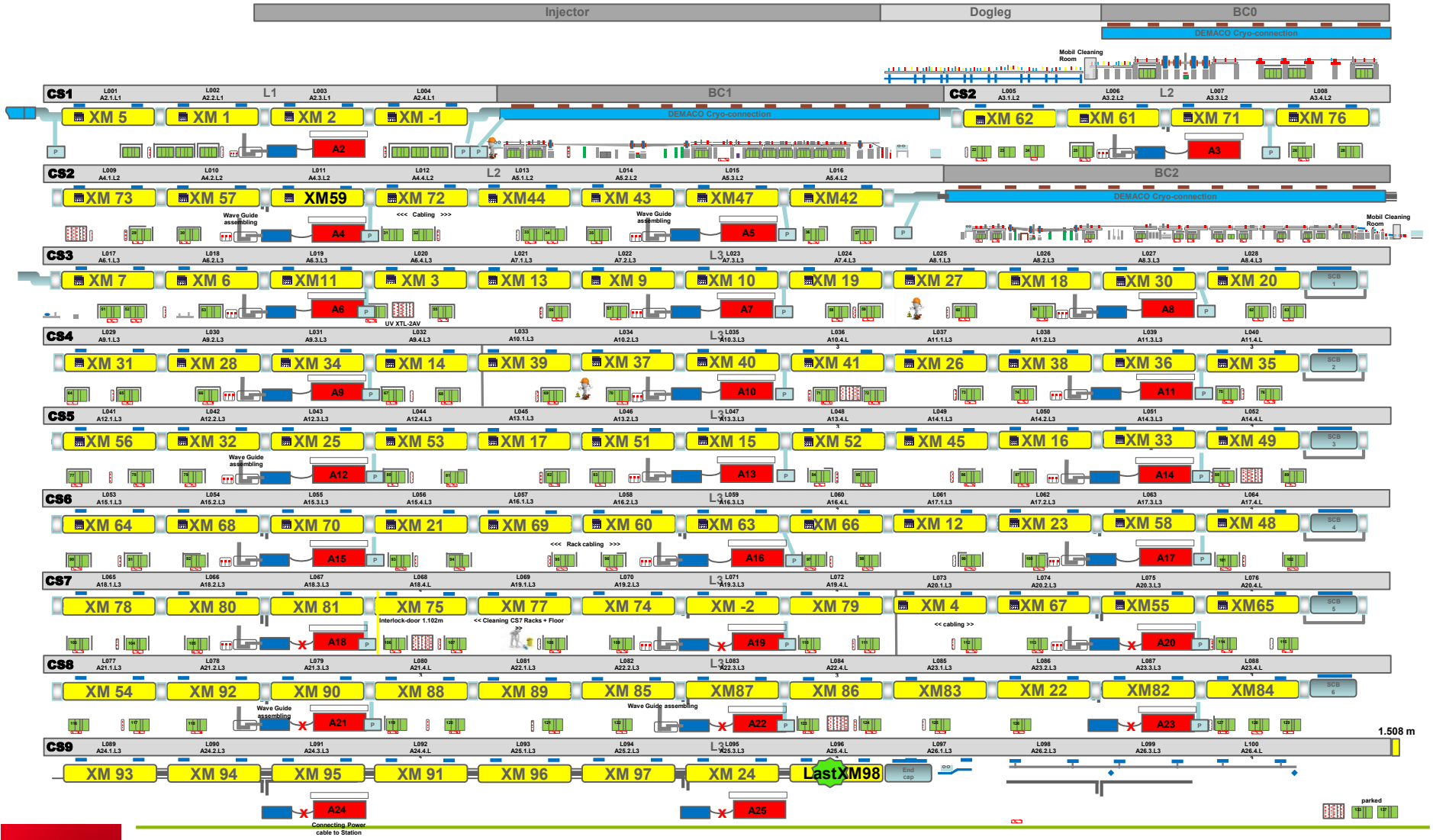
- **103 modules delivered to DESY** (incl[ing] XM-3, XM-2, XM-1).
- In 2015, one cryomodule was delivered every 4 days, 52 in total.
- The Cold Linac includes also two pre-series cryomodules: XM-2 and XM-1
- The shipment of XM100 was on 27 July 2016

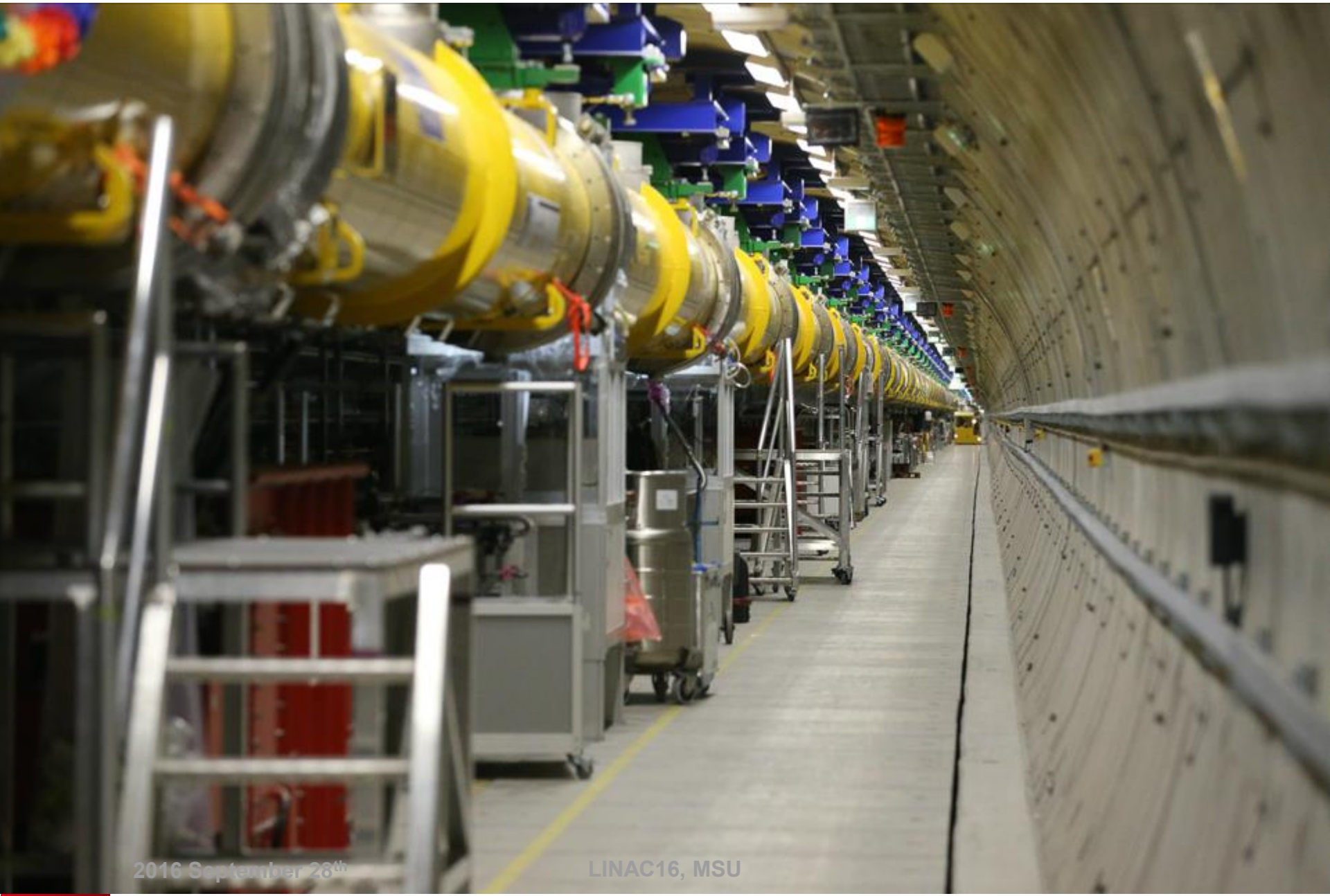
Installation Progress XTL

96 Modules installed

1 RF-Station ready
23 RF-Station in preperation

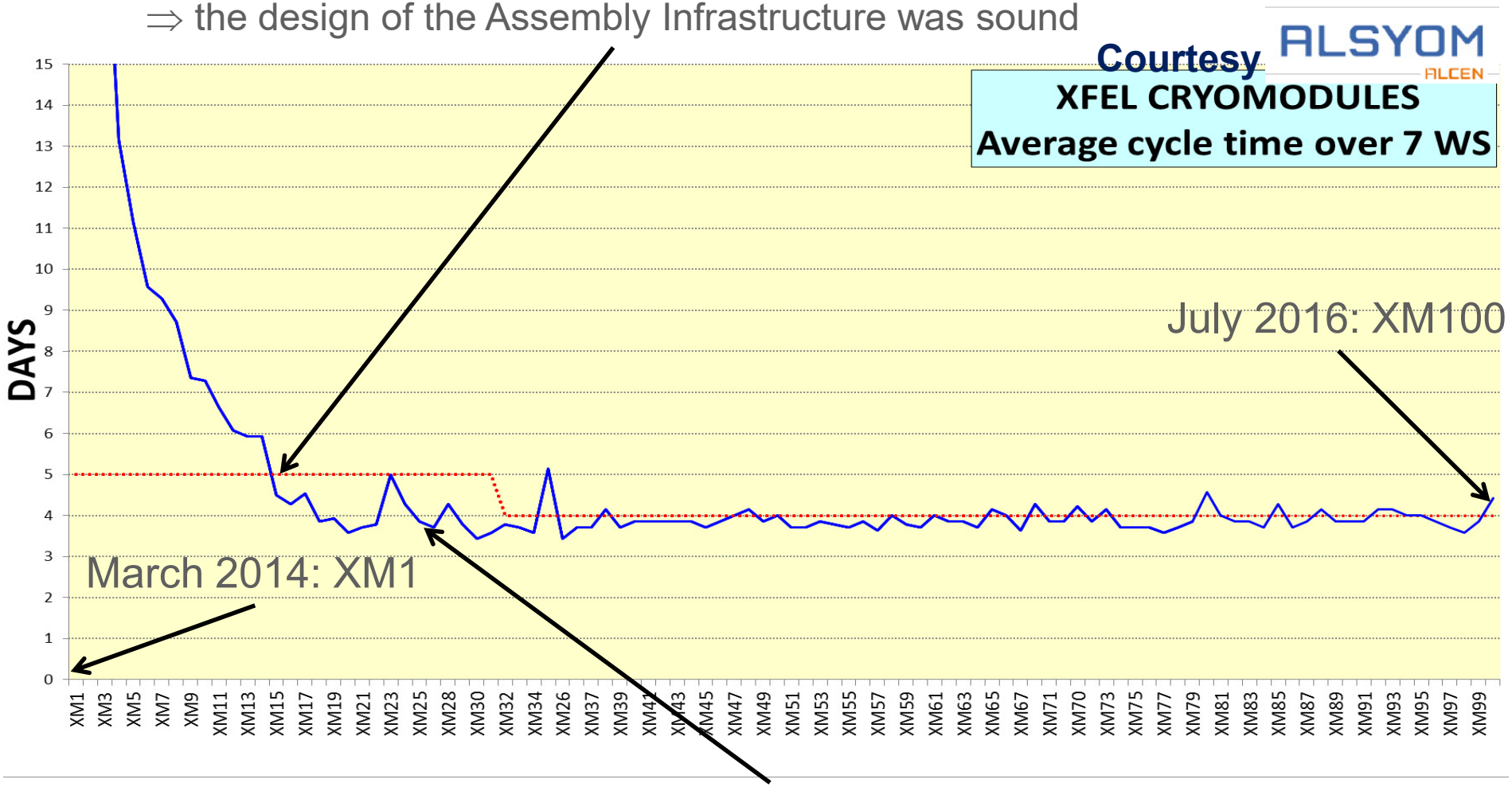
Status:
16.09.2016





Production Throughput

- 5 days throughput was reached **mid-October 2014** with **XM15**
  ⇒ the design of the Assembly Infrastructure was sound

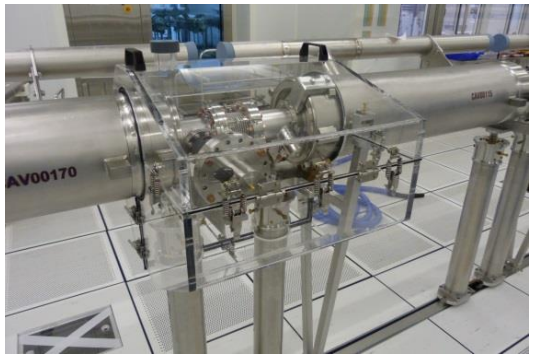


- 4-day throughput was reached **in January 2015** with **XM25**

Improving Integration Processes

Acceleration and Quality of Production benefited mostly from:

- New clean room assembly procedure: moving individual cavity venting after the leak check of the cold coupler assembly, rather than later, before the string assembly. This eliminates one connection to pumping stations for cavity venting, and one valve closing-opening cycle.
- New equipment, e.g. string leak test plexi-box:

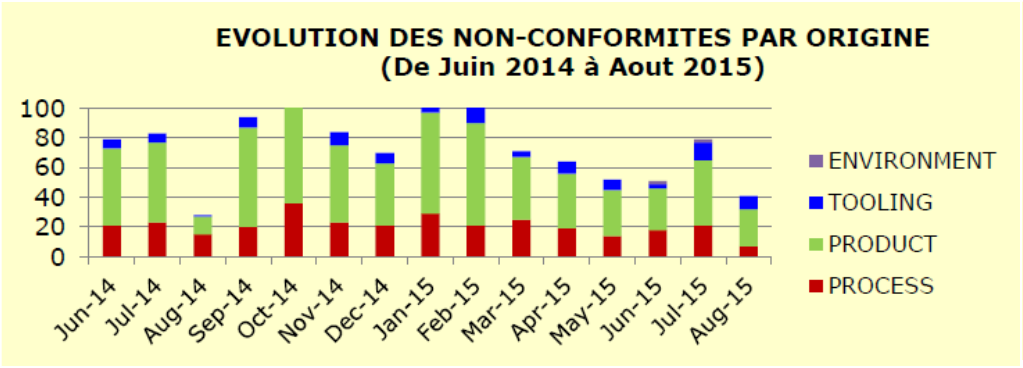


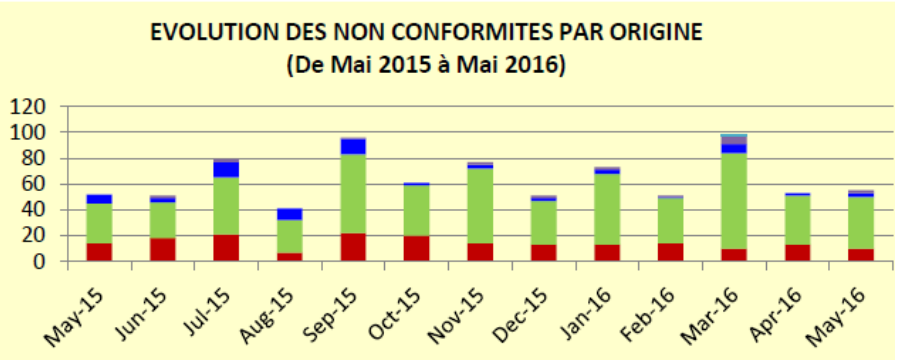
- Pure Argon gas for Titanium welding, instead of He-Ar (50%-50%), to avoid the long and unpredictable time to pump and purge the LHe tank to reach the He background for the leak test (LT) by external accumulation.
- Reducing the impact of non-conformities, particularly imported NC.
  More human resources have been put on incoming inspection and QC.

Quality Control: Non Conformities

Non Conformities recorded by Alsyom fall into 3 categories:

1) Tooling and equipment (TOOLING), responsibility by CEA/DESY
2) Accelerator components (PRODUCT), responsiblity by suppliers
3) Assembly operations (PROCESS), responsibility Alsyom





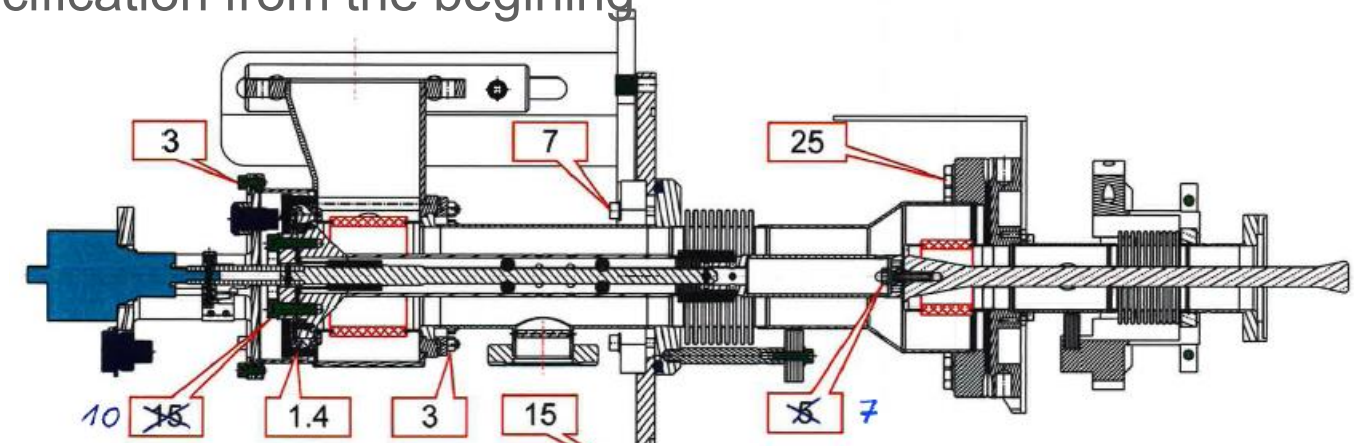
The number of PRODUCT Non-Conformities has not gone down.

But, with better and more efficient detection at incoming inspection, the impact of PRODUCT NC on the module assembly has considerably decreased, compared to when many NC were discovered ‘on the fly’.

Quality Control

XFEL coupler screws torques [N·m]

Ask for torque specification from the begining



Irfu cea

1	Numéro de série du cryomodule:				XM	99			
	Position:	#1	#2	#3	#4	#5	#6	#7	#8
2	Contrôle de la fixation de la partie chaude du coupleur sur la partie froide: Couple = 25N.m⁻¹	OK	OK	OK	OK	OK	OK	OK	OK
	Nom du controleur:	RL	RL	RL	FD	RL	RL	RL	RL
3	Contrôle de la fixation de la partie chaude du coupleur sur la partie froide: Couple = 25N.m⁻¹	OK JPC	OK JPC	OK	OK	OK JPC	OK JPC	OK	OK
	CEA Nom du controleur:			TA	JLP			RL	JLP
4	Contrôle du serrage de la vis centrale: (Antenna screw) Couple = 7N.m⁻¹	OK 7N/m JPC	OK	OK	OK	OK 7N/m JPC	OK 7N/m JPC	RC OK	OK 5N/m
	CEA Nom du controleur:		RS		JLP				JLP
5	Reprise du taraudage de la vis centrale o/n :					11/07/16			
	CEA Nom du controleur:					JPC			
6	Contrôle du serrage du Push Rod: Couple = 10N.m⁻¹	OK							
	Nom du controleur:	RL							

Alsyom QC

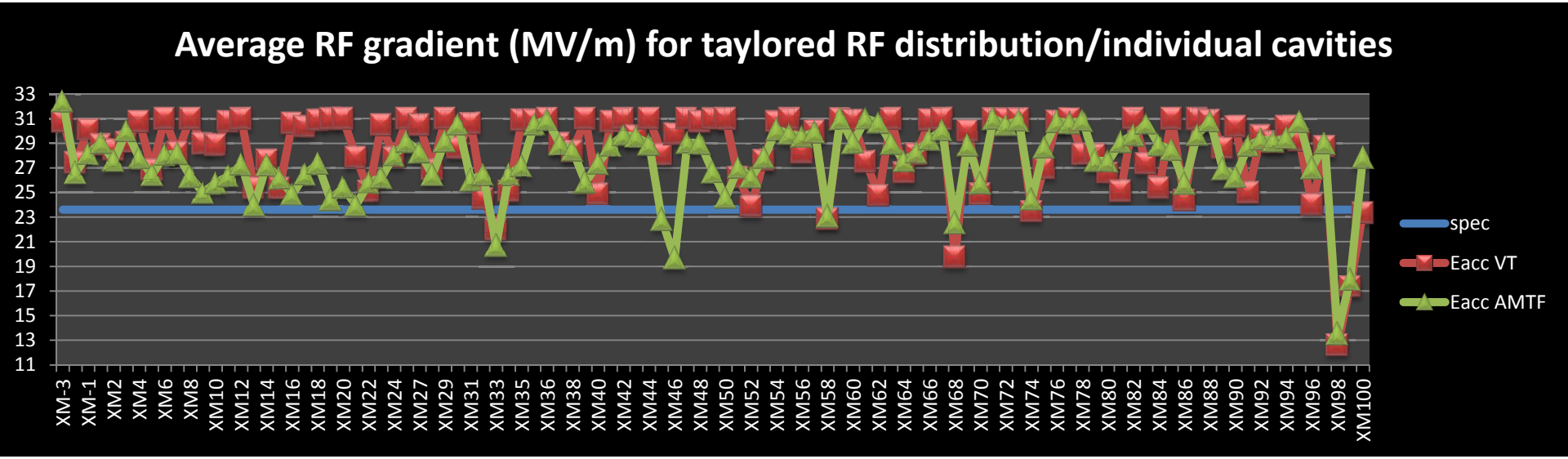
CEA QC

Le 21/08/2014
T. TRUBLET

The Quality Control of QC is needed !

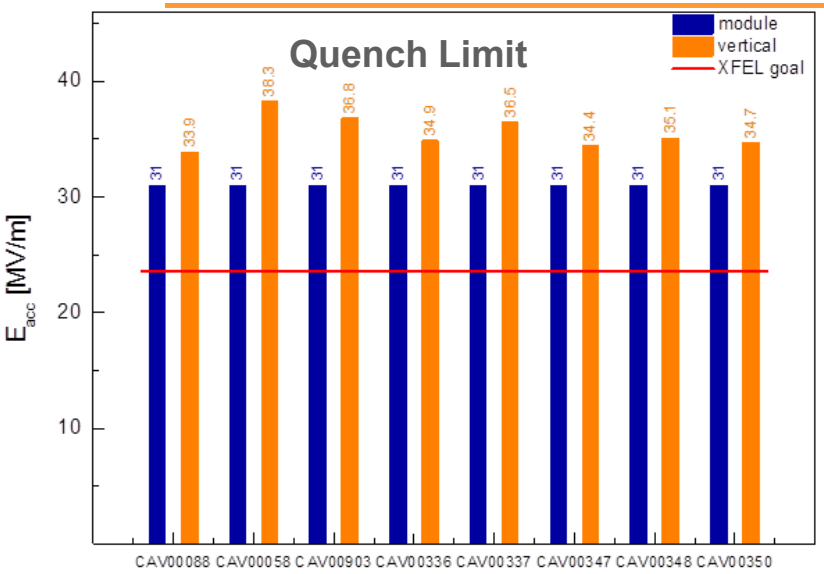
Cryomodule Performance at AMTF

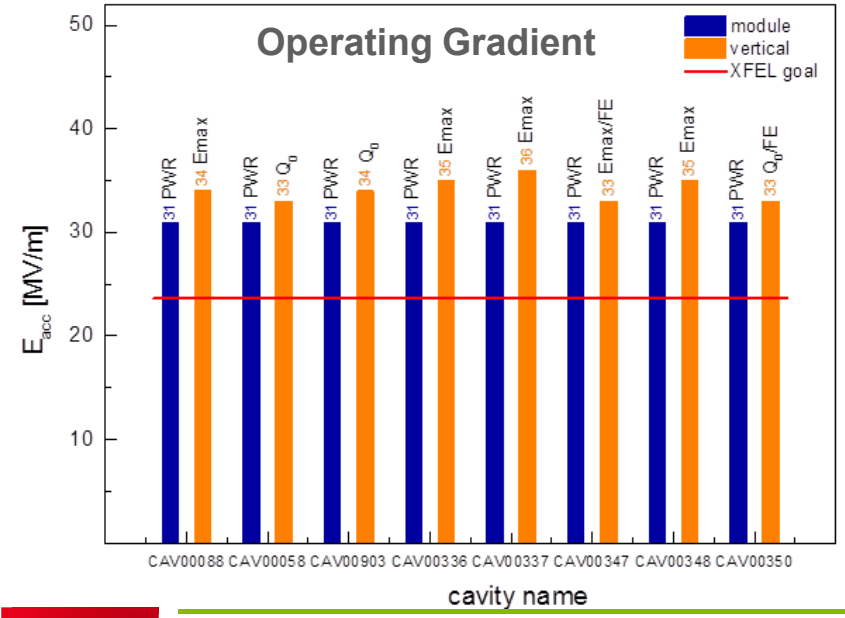
Average operating gradient per cryomodule, clipping the VT results to 31 MV/m

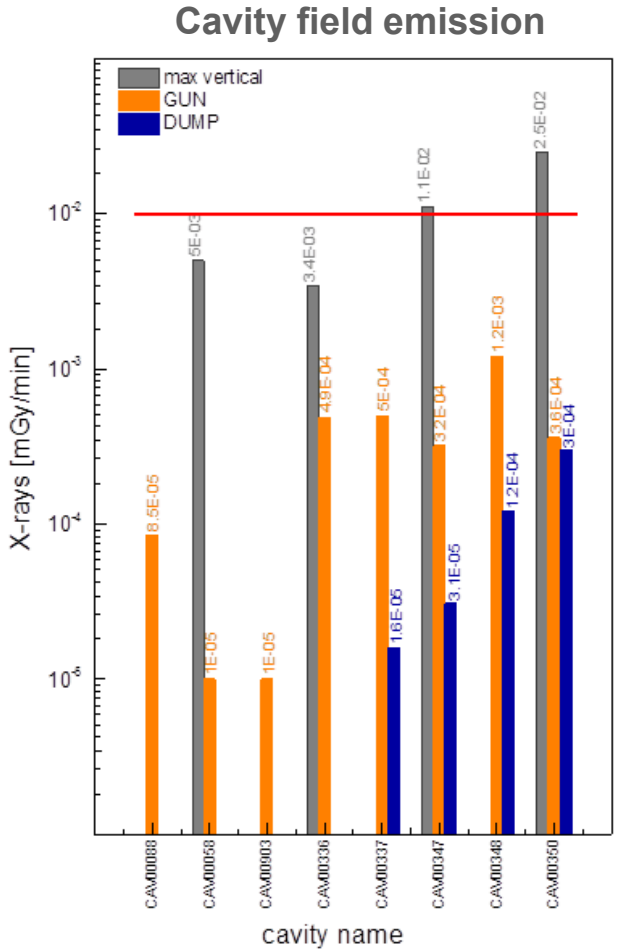


- AMTF average gradient is 18% above specs : $\langle E_{acc} \rangle$ **= 27.8 MV/m**.
- All but 7 of 103 tested modules are on XFEL specs (23.6 MV/m):
  - XM33, XM58 XM68 XM98 and XM99 are limited by individual cavity performance
  - XM45 was impacted by a clean room power outage
  - XM46 was impacted by beam vacuum leaks

XM71 Performance





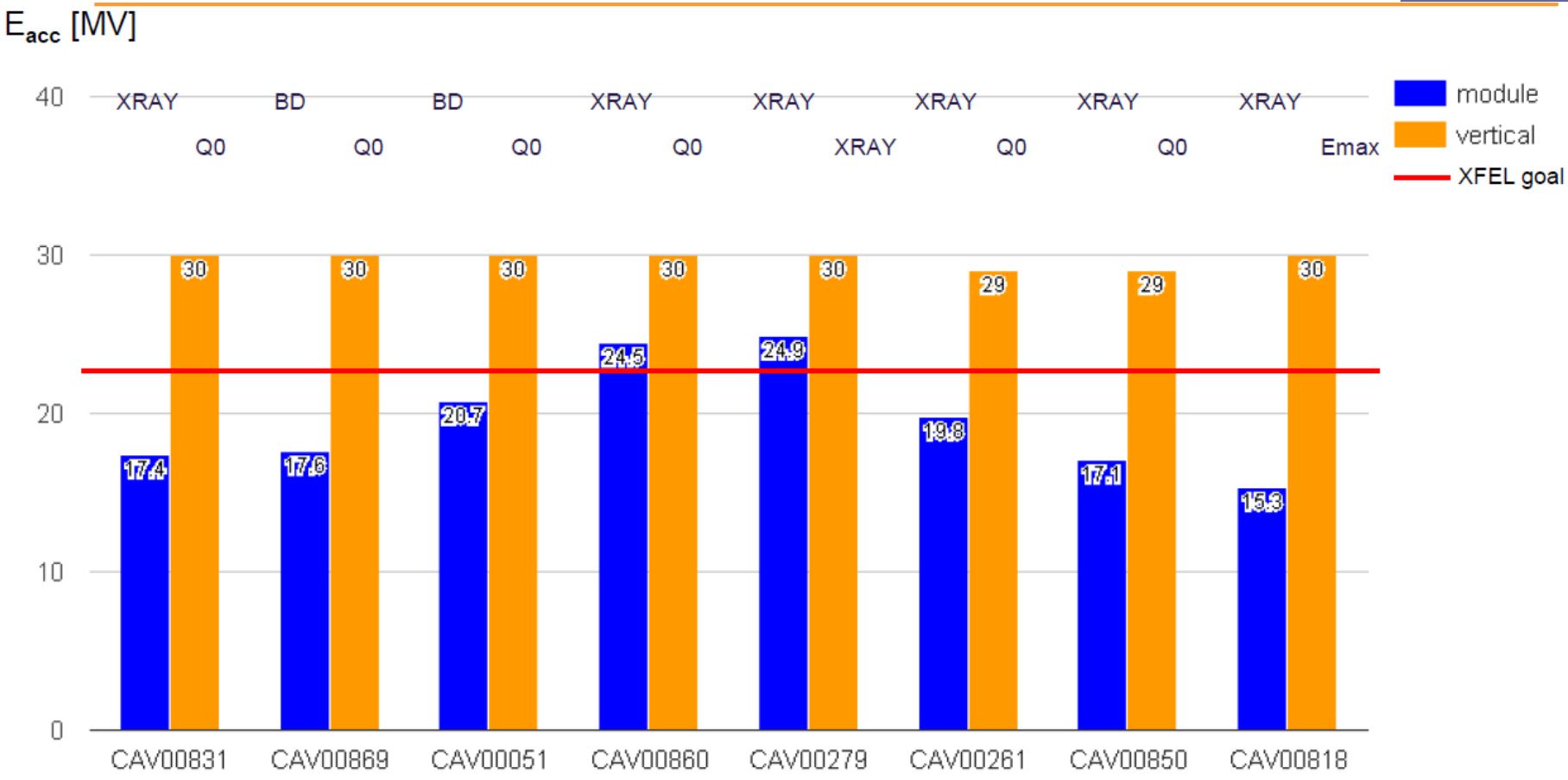


VT @ 34-38 MV/m

MT @ 31 MV/m

Cavities 2,4, 6 and 8 have higher field emission in VT (@quench limit gradient) than in AMTF (@ 31 MV/m power limit).

Cryomodule Performance : XM46



$\langle E_{acc} \rangle$ = 19,7 MV/m

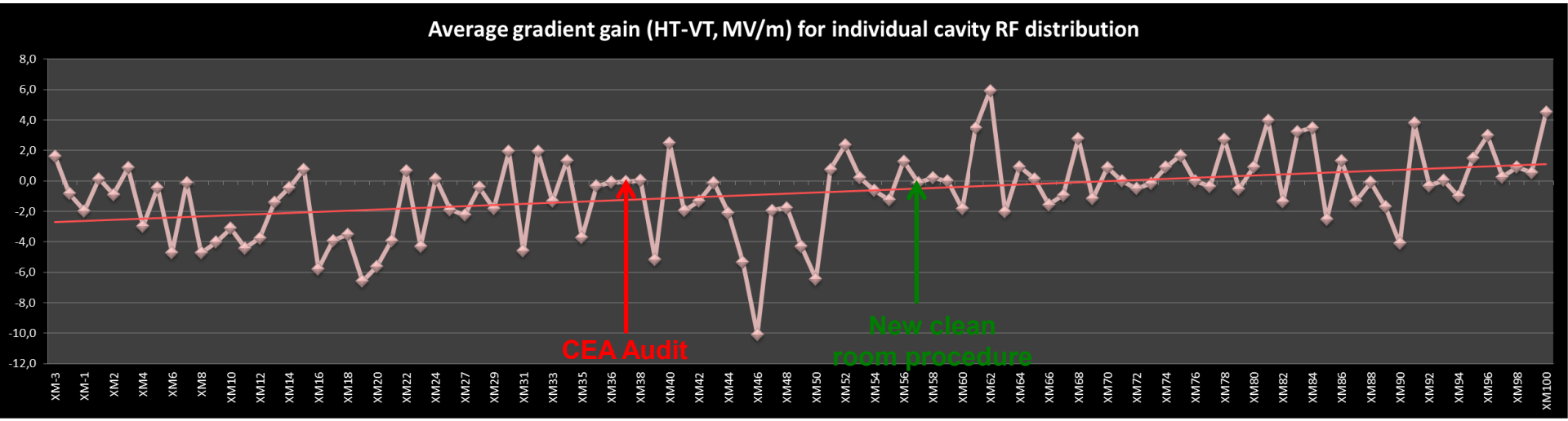
XM46 string was **leaky in the clean room AND before shipment**. Both leaks have been repaired at Saclay but they generated 2 extra connections of the beam vacuum to pumping groups, and 2 additional venting-pumping

About Gradient Comparison

- Accelerating gradients are the most scrutinized mod… performance parameters, although heat loads, alignment and …tification are entering the acceptance criteria.
- The absolute gradient is the result of t… chain, from the Nb sheet to the module t… determined by **cavity manufacturing** and …
- The quality of module… gradient difference between cavity a… module acceptance (MT).
- The VT vs. A… the 'maximum' and the 'operati… paired by a **systematic error:**
  1. Maxi… pend on 1) RF duty cycle, 2) cooling conditions and, 3) mag… ment, which are completely different from VT to MT
     → *m… cavity-independent error*
  2. Operational gradients depend, **in addition,** on X-Ray measurement devices which are different from VT to MT (although cross-calibrated)
     → *mostly cavity-independent error*
  3. Finally, Q_0 is not measured in MT: therefore the MT usable gradient could correspond to **lower** or **higher** Q_0 values → *cavity-dependent error*

See Nick WALKER's presentation : Performance Analysis of the European XFEL SRF Cavities, From Vertical Test to Operation in Models

Cryomodule Performance: VT vs. MT



1st sample of 34 series CM
ΔE_{op} = -2.1 MV/m

2nd sample of 19 series CM
ΔE_{op} = -1.7 (-0.9) MV/m

last 48 series CM
ΔE_{op} =+0.4 MV/m

- Significant gradient degradation from XM6 to XM23, while CEA and Alsyom put all their effort in achieving production goal of 1 CM/week: an audit of string and module assembly was conducted by CEA on XM26
- A simplification of the clean room procedures was introduced at XM54: **no degradation after**

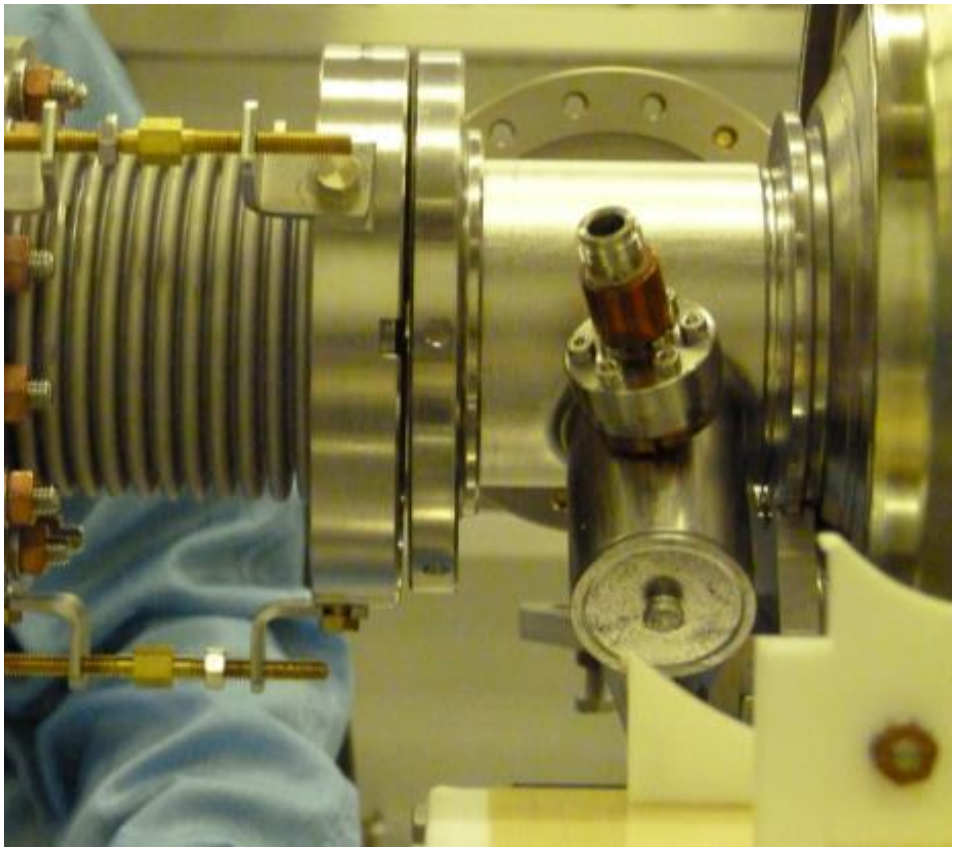
XM26 Clean Room Assembly Audit

Audit Findings:

- Operators walk too fast in the clean room.
- Record the cleanliness level (< 10 particles / min) reached on the angle valve before the pump connections to the cavity (CC and SA).
- Two operators are requested to connect cavity to the pumping system (CC and SA).
- Two operators are requested to position inter-cavity bellows and screw first 4 studs (SA).
- Careful pre-alignment of parts (coupler and cavity flanges at CC, inter-cavity bellow/cavity-coupler-side flange at SA) is requested for easy and clean assembly.
- Improvement of operator positions versus critical RF surfaces (avoid top assembly, request seated).
- Gate valve connection to pumping system procedure has been reviewed to ensure better cleanliness (CC).

SA-WS: pre-alignement of bellows

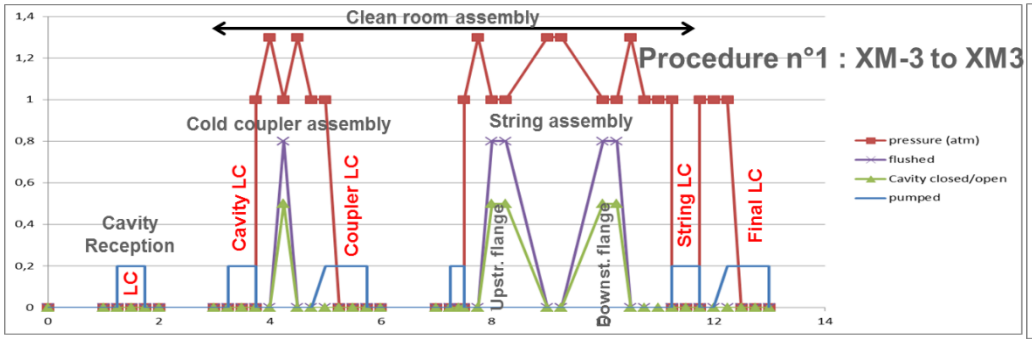
Observation during XM26 assembly

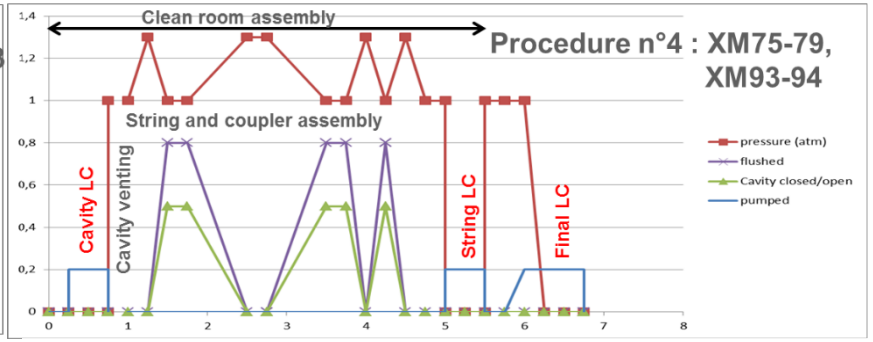


Clean Procedures: Comparison

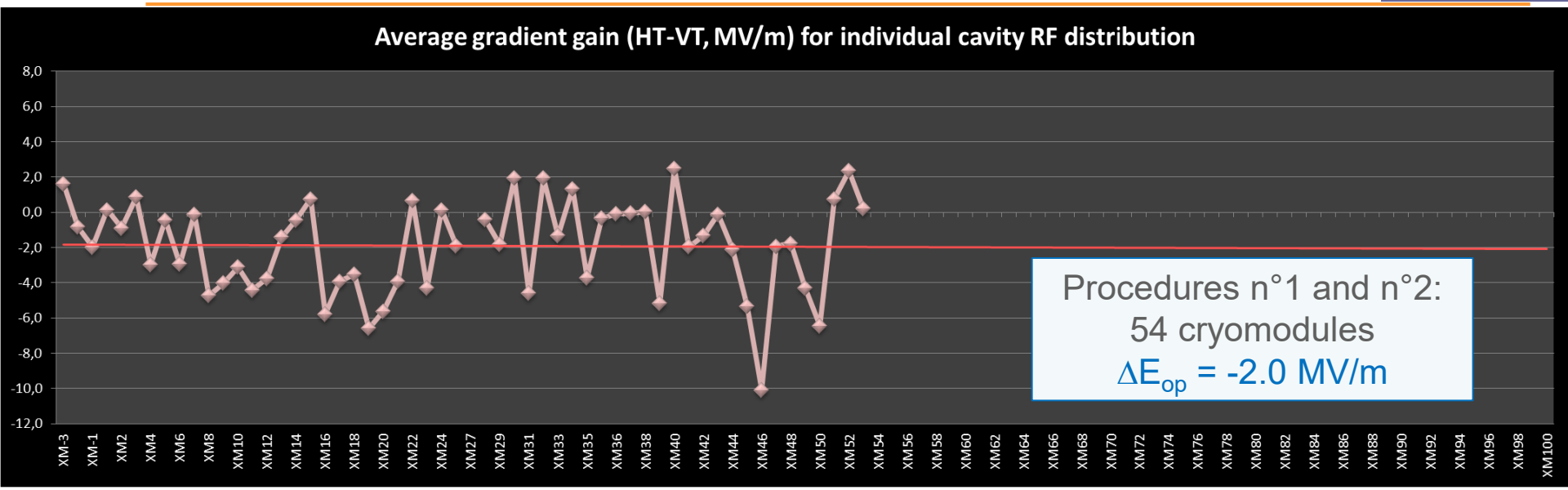
Number of vacuum operations for a complete cryomodule assembly

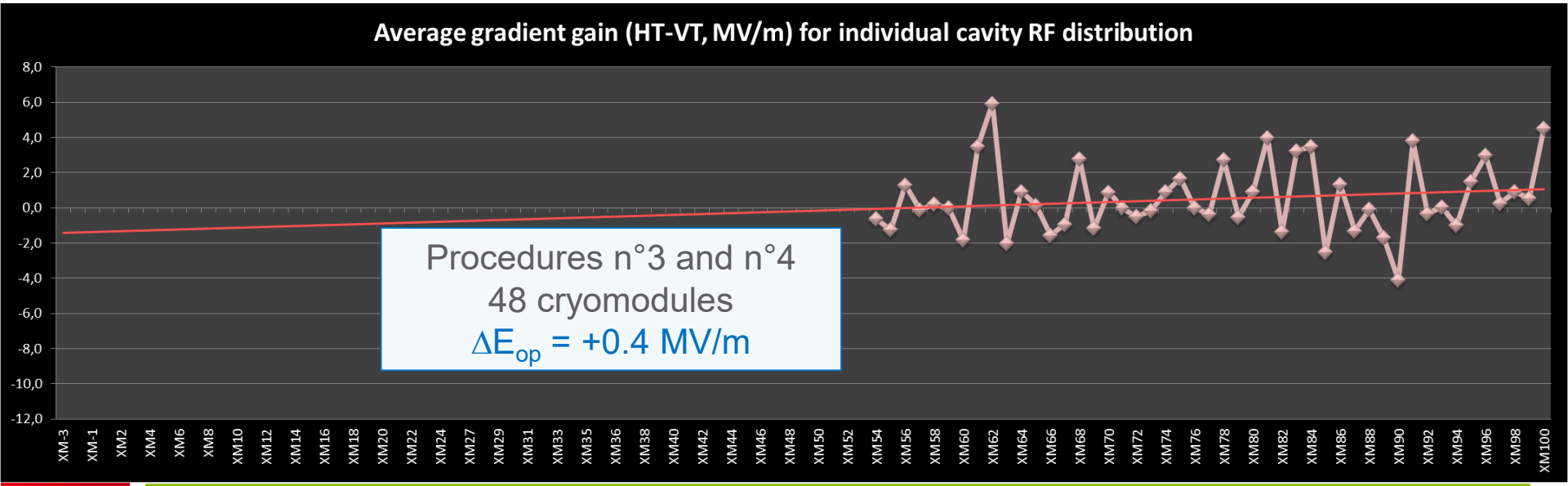
Procedure	n°1	n°2	n°3	n°4
# Gate valve to pipe connections	34	22	14	14
# Gate valve open/close cycles	33	21	13	13
# N2 blowing after an opening	17	17	9	9
# Leak checks	52	40	32	23





Cryomodule Performance: n°1-2 vs. n°3-4





Conclusions for Cryomodule Assembly

- E-XFEL Cryomodule Assembly at Saclay implied 4 main overlapping phases:
  1. Mastery of assembly procedures [T1/2008 – T1/2013], with XM-3
  2. Mastery of infrastructure and tooling [T3/2010 – T1/2013], at XM-1
  3. Mastery of non-conformities handling, both *imported*-PRODUCT and PROCESS-*generated* non-conformities [T3/2012 – T3/2014], at XM15
  4. 'Mastery' of the industrial operator
     - Productivity [T1/2014 – T4/2014], at XM25
     - Quality Assurance [T4/2014 – ongoing]

  This process depends on the early availability of the cryomodule components: '*Practice makes perfect*'
- The difficulties and the risks of coupler assembly had been under-estimated by CEA, especially for the coupler warm part
- Better module RF performance is correlated to Clean Room practice and Clean Room procedures.
- The goal of 'zero mistake' has been missed: the rate of ~ 1 major mistake every 2 weeks is an organisational problem.

Conclusions (2/2)

- E-XFEL Cavity production demonstrates the existence of EU vendors for cavities in the range 30 – 40 MV/m.
- E-XFEL AMTF demonstrates that RF testing is feasible) at a rate compatible with one ILC hub, even if 100% MT is the chosen option: 11-day cycle per module, with 3 MT bunkers in AMTF
- E-XFEL Cryomodule Assembly demonstrates that a 3-day throughput is feasible for ILC production, leading to about **120 modules per year** on one production site.
- When all assembly equipments are operating under nominal conditions, there are clear indications that RF performance of the cryomodules is impaired by:
  - The invasiveness of operators in the clean room
  - The invasiveness of vacuum operations on the beam vacuum. Both can be mitigated with good quality control and floor inspections
- Clean room assembly can be further improved, qualitatively and quantitatively, e.g. by unifying cold coupler and string assembly in a unique workstation (2 shifts required to achieve 3-day throughput).

Acknowlegments for Module Integration

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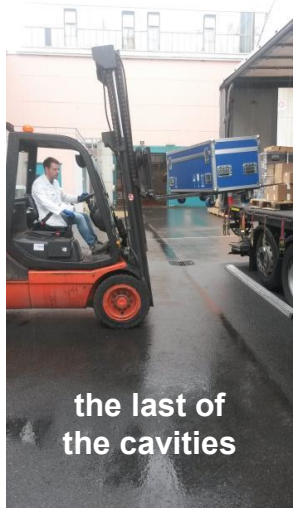

Thank you for your attention