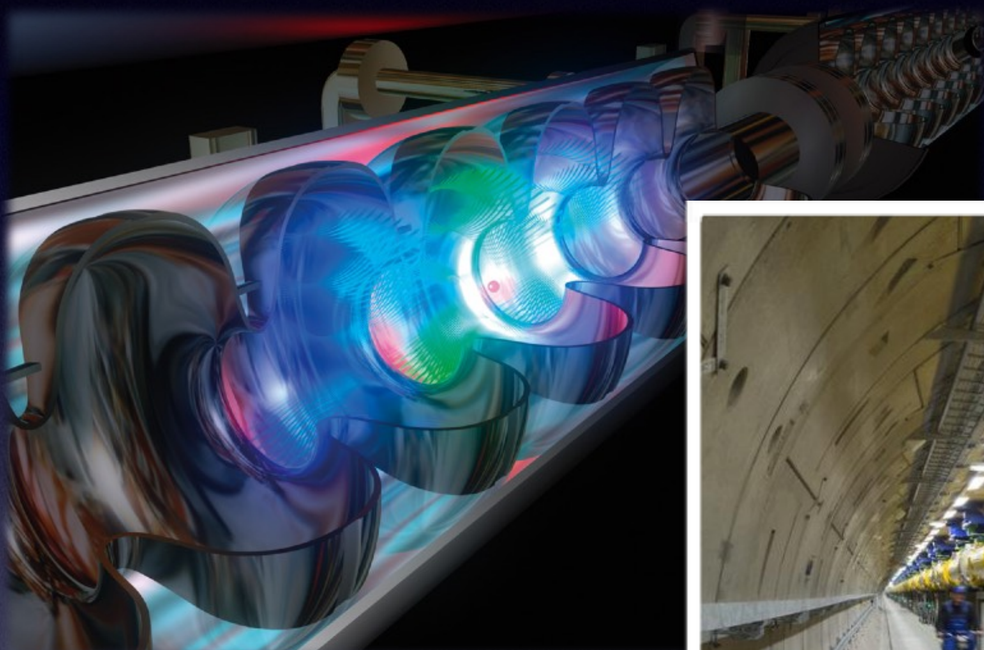
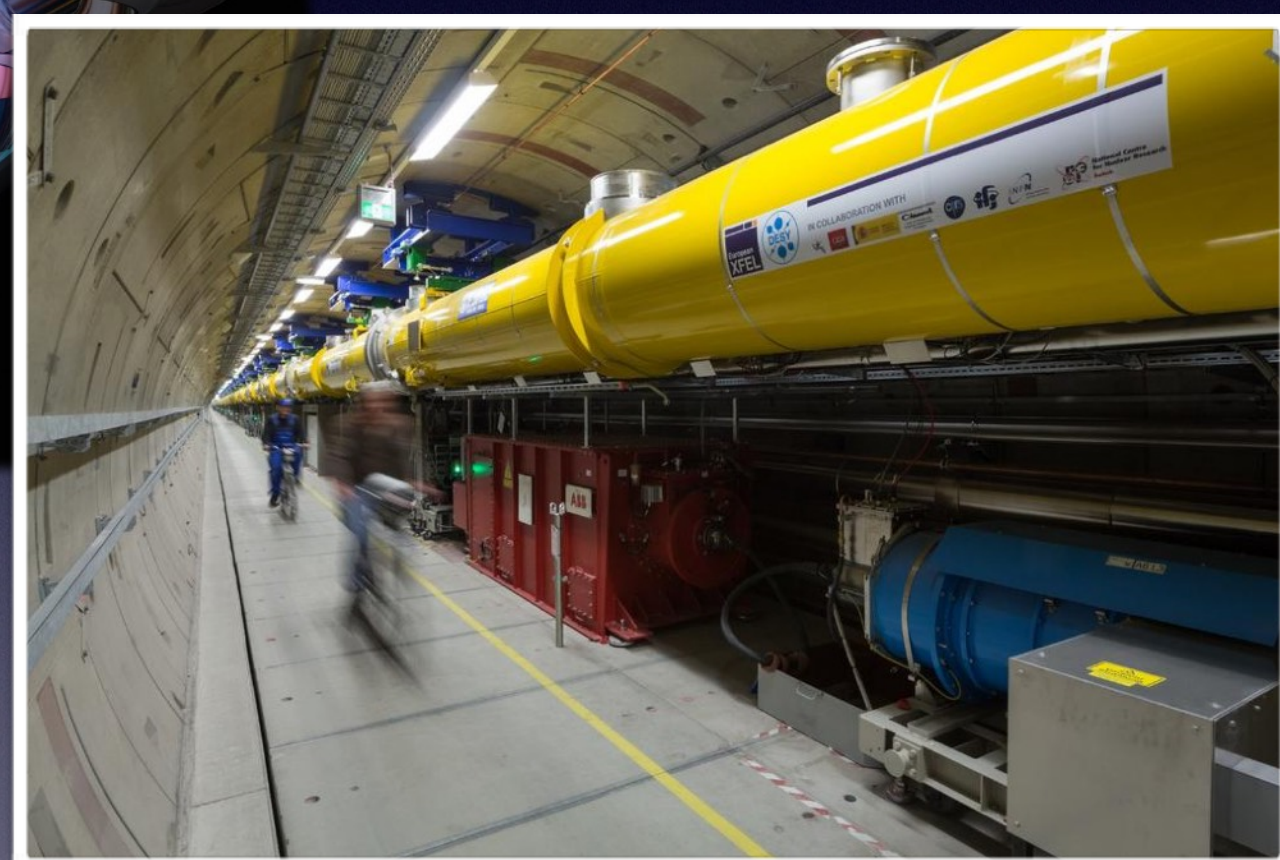
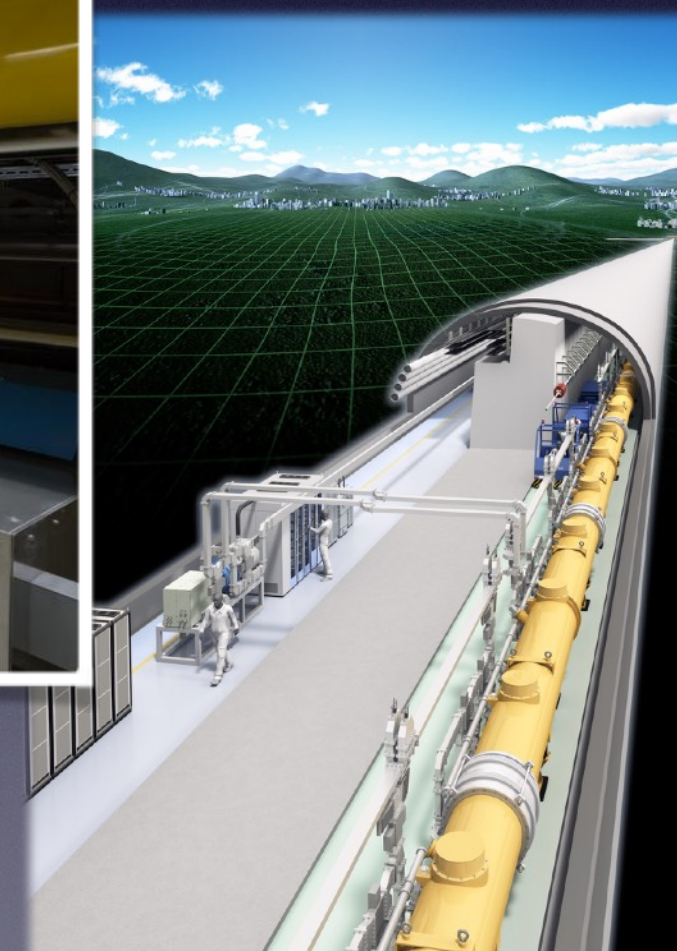
From Linear Collider to European XFEL
(and back again)







Nick Walker - DESY

Oxford, 13th February, 2017

Introduction

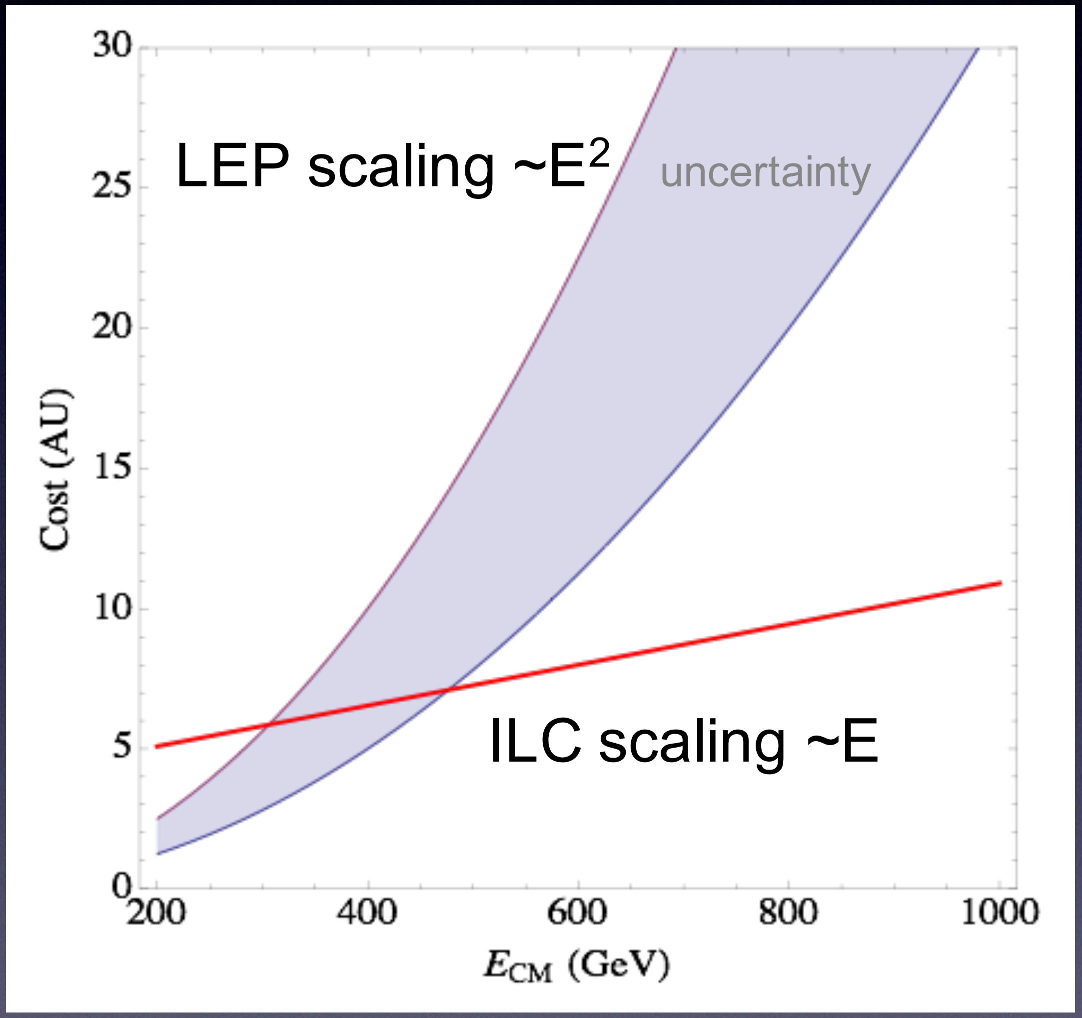
- A history of the (I)LC (over 20 years ..and counting)
- A history of TESLA 1.3 GHz SRF technology
- Status (and results) of the European XFEL
  - extrapolation to ILC
- ILC —what's next?

So why a Linear Collider?

- Synchrotron Radiation

$$\Delta E / rev = \frac{C_\gamma E^4}{\rho}$$

- Cost "optimum" scaling
  - Cost ~E^2
  - Radius ~E^2
  - MWatt ~E^2



One can argue about where the cross-over point is,
but the ultimate future of e^+e^- energy-frontier colliders is linear
(or not at all).

An Old Idea

A Possible Apparatus for Electron-Clashing Experiments (*).

M. Tigner

Laboratory of Nuclear Studies. Cornell University - Ithaca, N.Y.

Nuovo Cimento 37 (**1965**) 1228

"*While the storage ring concept for providing clashing-beam experiments is very elegant in concept it seems worth-while at the present juncture to investigate other methods which, while less elegant and superficially more complex may prove more tractable.*"

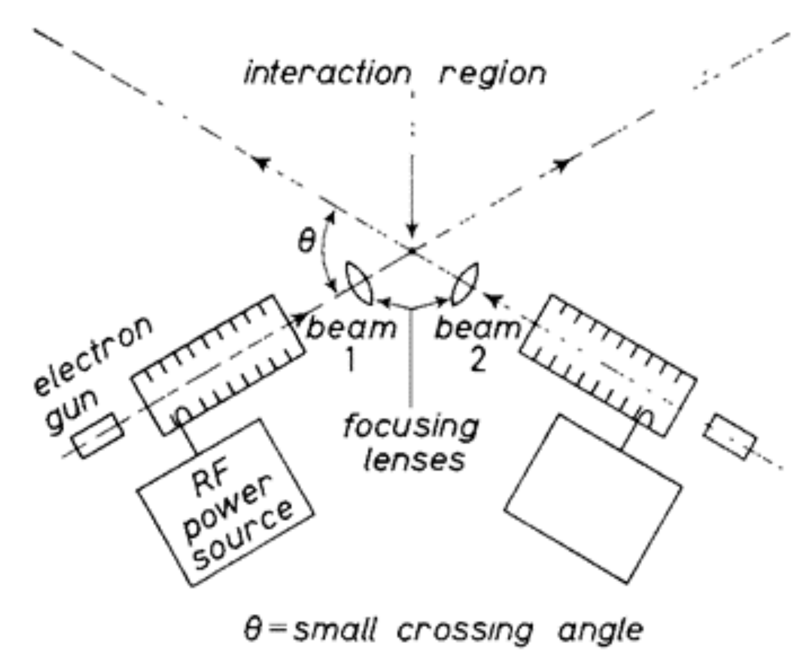


Fig. 1.

The real start of the story

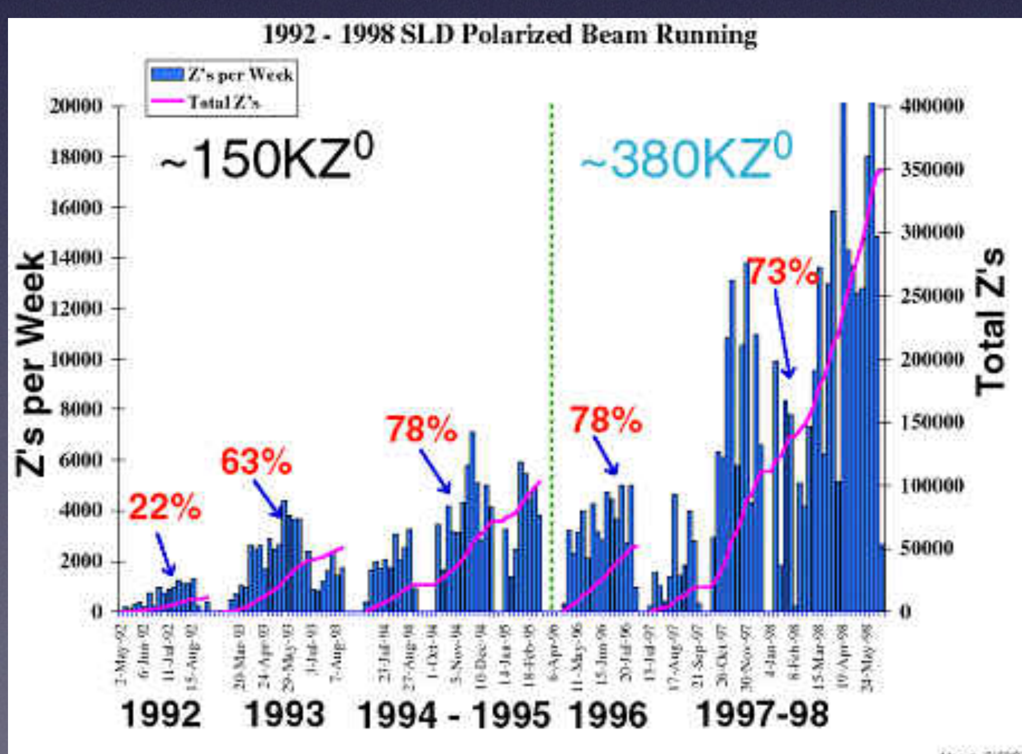
Burt Richter

SLAC Linear Collider (SLC)

E_{cm} ~ 90 GeV

1989-1998

A proof of principle



Evolution

1994

Technology Review Committee (TRC) I

TESLA (DESY)	1.3 GHz
SBLC (DESY)	3.0 GHz
JLC-S (KEK)	2.8 GHz
JLC-C (KEK)	5.7 GHz
JLC-X (KEK)	11.4 GHz
NLC (SLAC)	11.4 GHz
VLEPP (IHEP)	14.0 GHz
CLIC (CERN)	30 GHz

Evolution

1994 Technology Review Committee (TRC) I		2003 Technology Review Committee (TRC) II	
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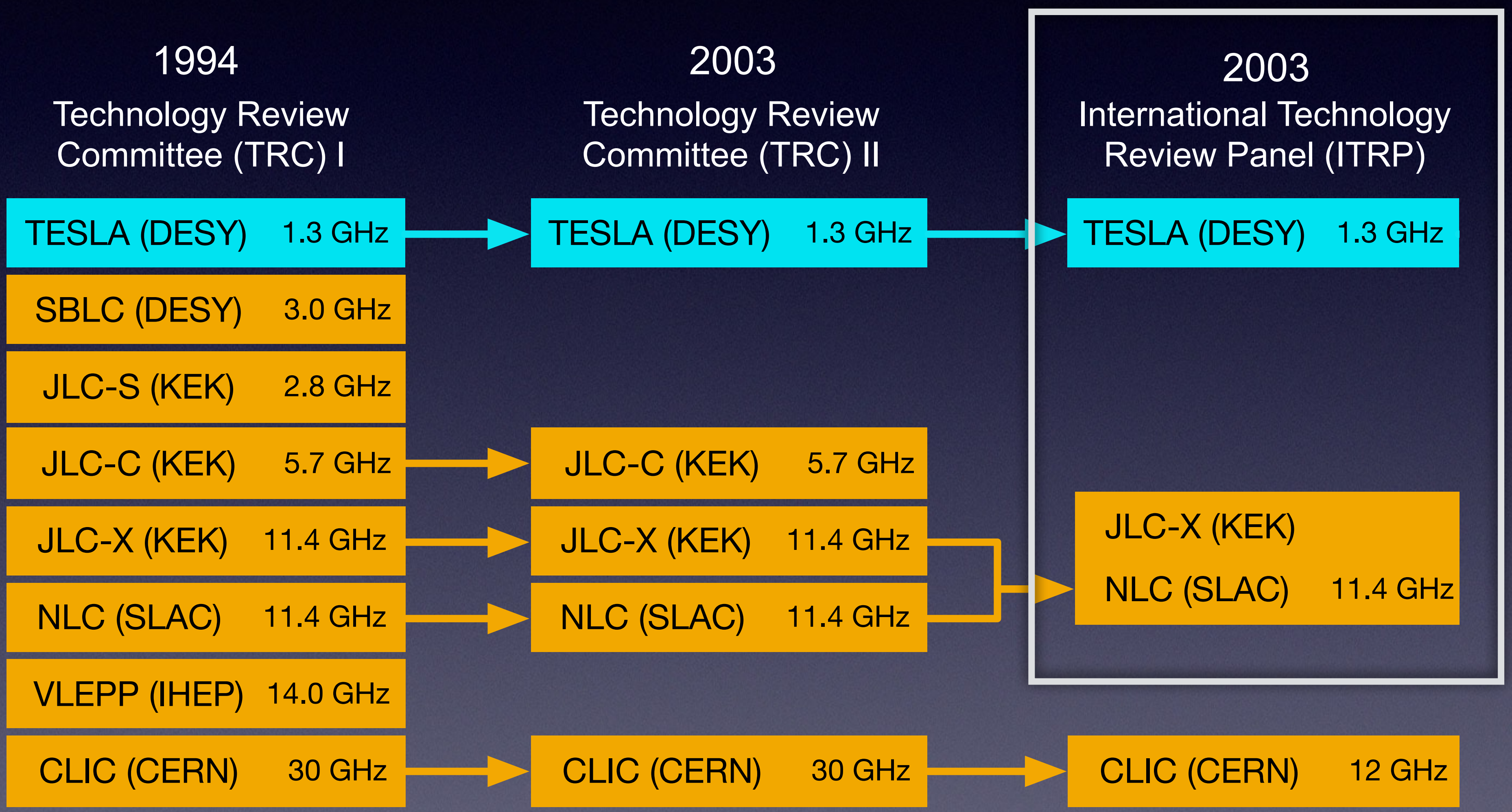
Evolution



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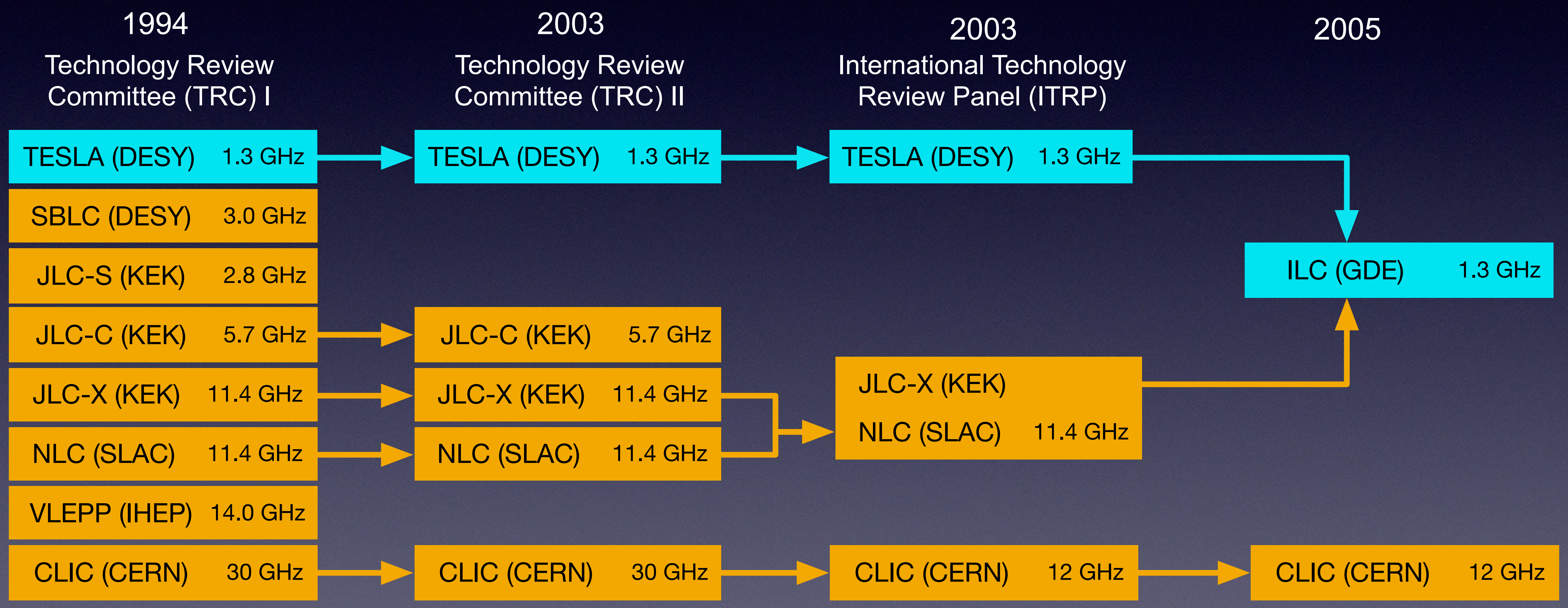
CLIC (CERN) 12 GHz

Evolution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ILC (GDE) 1.3 GHz
CLIC (CERN) 12 GHz

Why SRF?

- Low-loss cavities
  - High RF→Beam-power efficiency
  - Lower operational costs

- Ease of RF power generation
  - low frequency (1.3 GHz)
  - Long pulse / fill time (1ms / 0.6ms)
  - Low peak power (≤10 MW)

- Emittance preservation
  - large cavity iris (low frequency)
  - low transverse and longitudinal wakefields
  - loose alignment tolerances

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Related

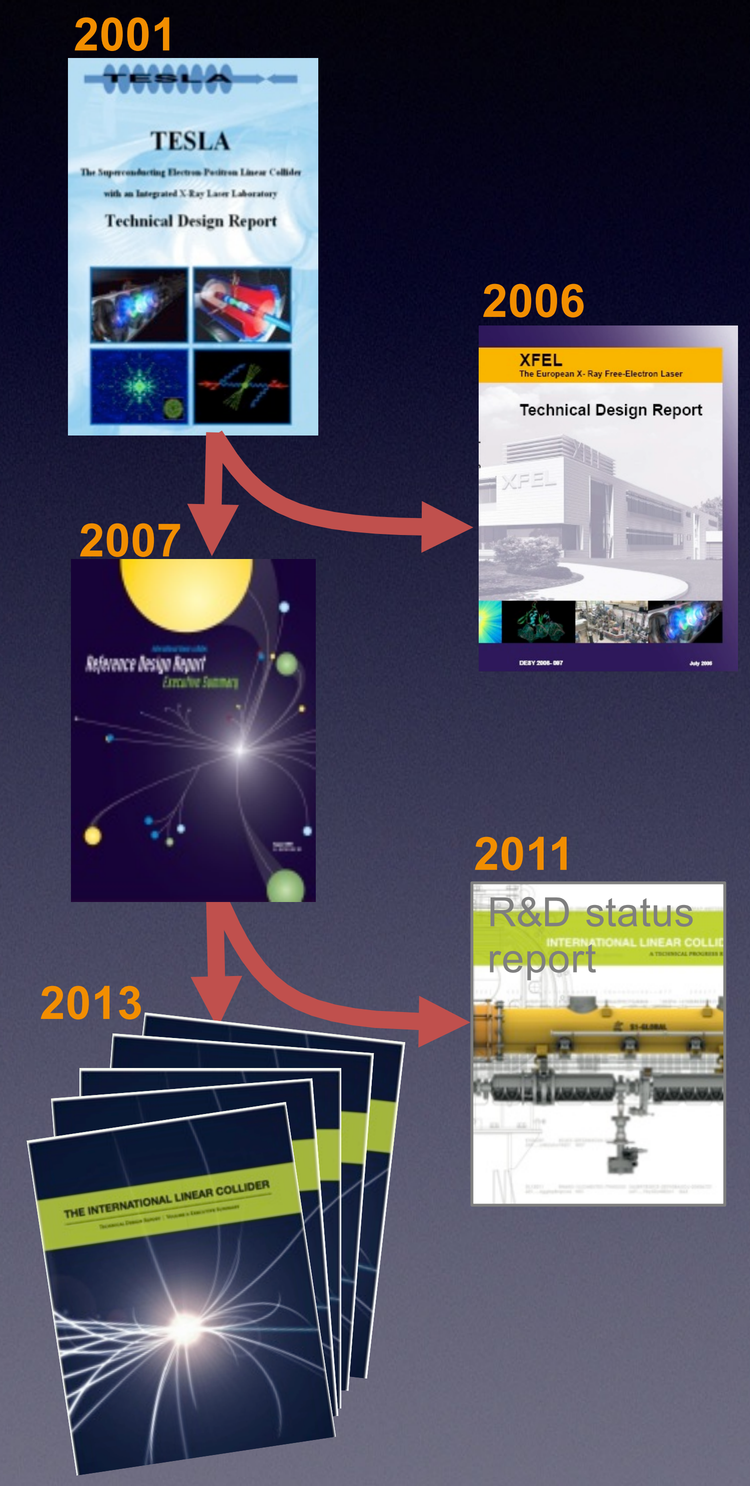
Why SRF?

“The construction of the superconducting XFEL free electron laser will provide prototypes and test many aspects of the linac.”

ITRP final report executive summary

ILC time line

- Pre Global Design Effort
  - 1992 TESLA starts
  - 2002 German BMBF XFEL decision
  - 2004 ITRP decision
  - 2009 XFEL construction begins
- Since 2005: GDE (B. Barish)
  - 2005-2007 Reference Design Report and cost estimate
  - 2008-2012 Technical Design Phase
  - 2012 TDR and updated cost estimate
- 2013-
  Linear Collider Collaboration (LCC, L. Evans) towards project realisation in Japan.



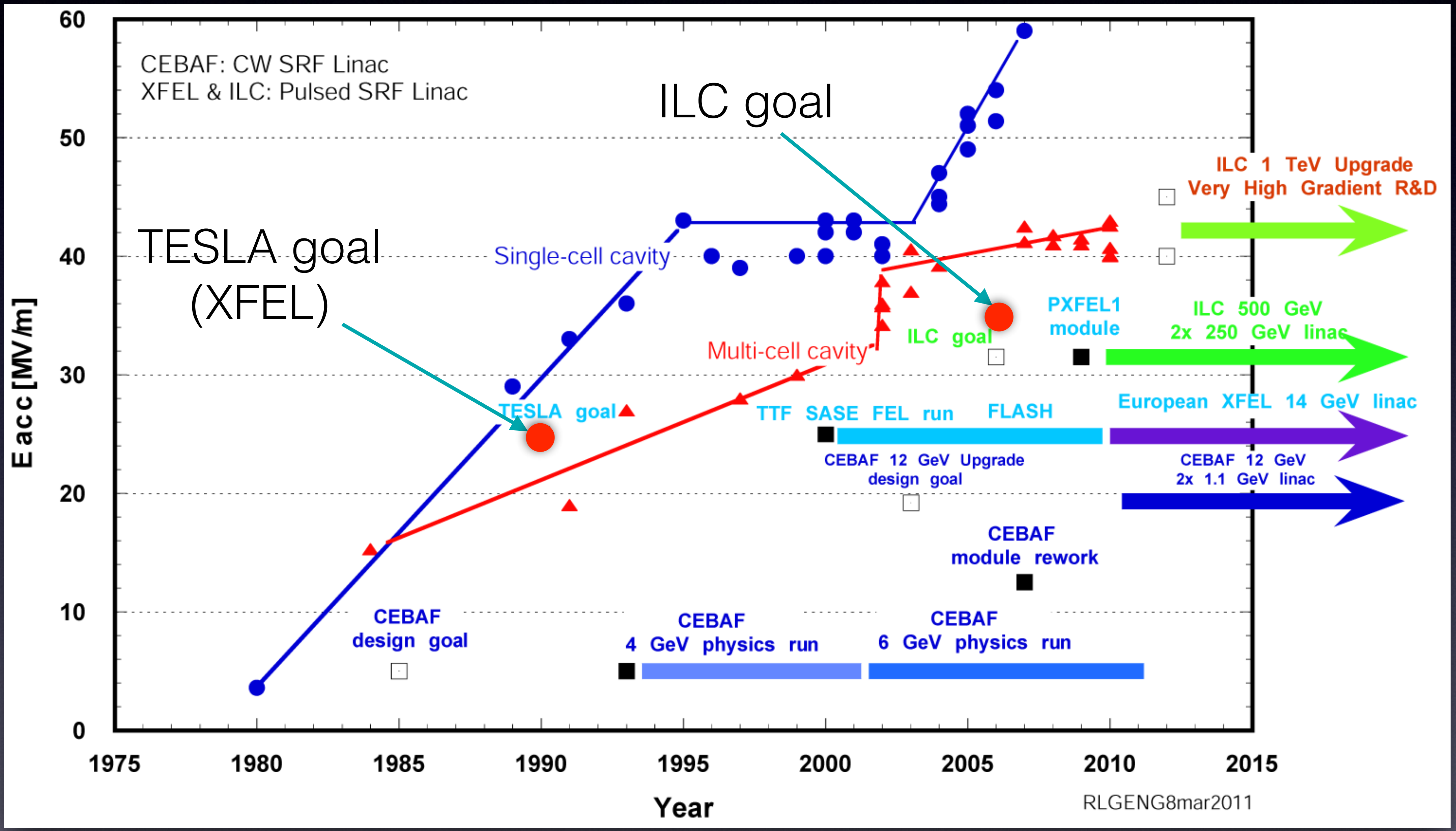
TESLA Technology



- 1.3 GHz solid niobium nine-cell resonator (cavity)

- 1990's goal: reduction in \$/MeV by a factor of 20
  - Factor 5 in gradient → 25 MV/m
  - Factor 4 from cryostat integration

The Quest for High Gradient



courtesy Rongli Geng

The path to high performance

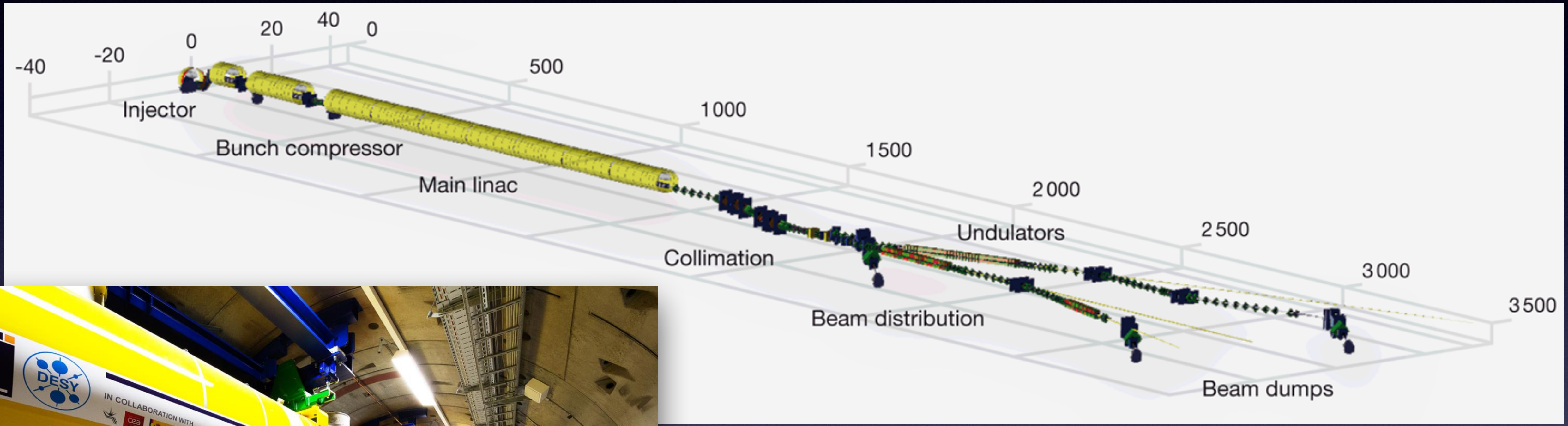
- Control of niobium material (high purity)
- Mechanical construction in a clean environment
  - electron-beam welding (EBW)
- Preparing RF (inner) surface ultra-clean mirror surface
  - electro-polishing (EP)
- Removing hydrogen from the surface layer
  - 800 deg C bake
- Removing surface contamination
  - alcohol and/or detergent rinsing
  - 100-150 bar high-pressure rinsing (HPR)

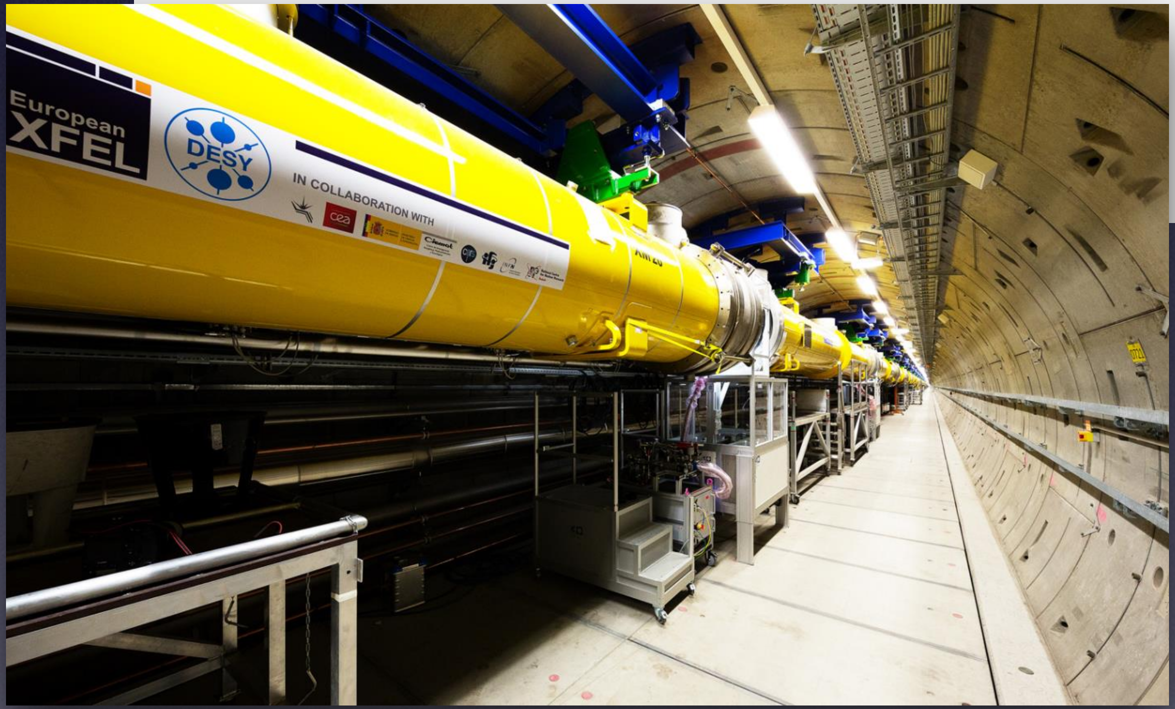
High gradient

High Q_0

Low Field Emission
(dark current)

European XFEL





100 cryomodules

→ 800 1.3 GHz 9-cell cavities

$\langle E_{acc} \rangle$ = 23.6 MV/m

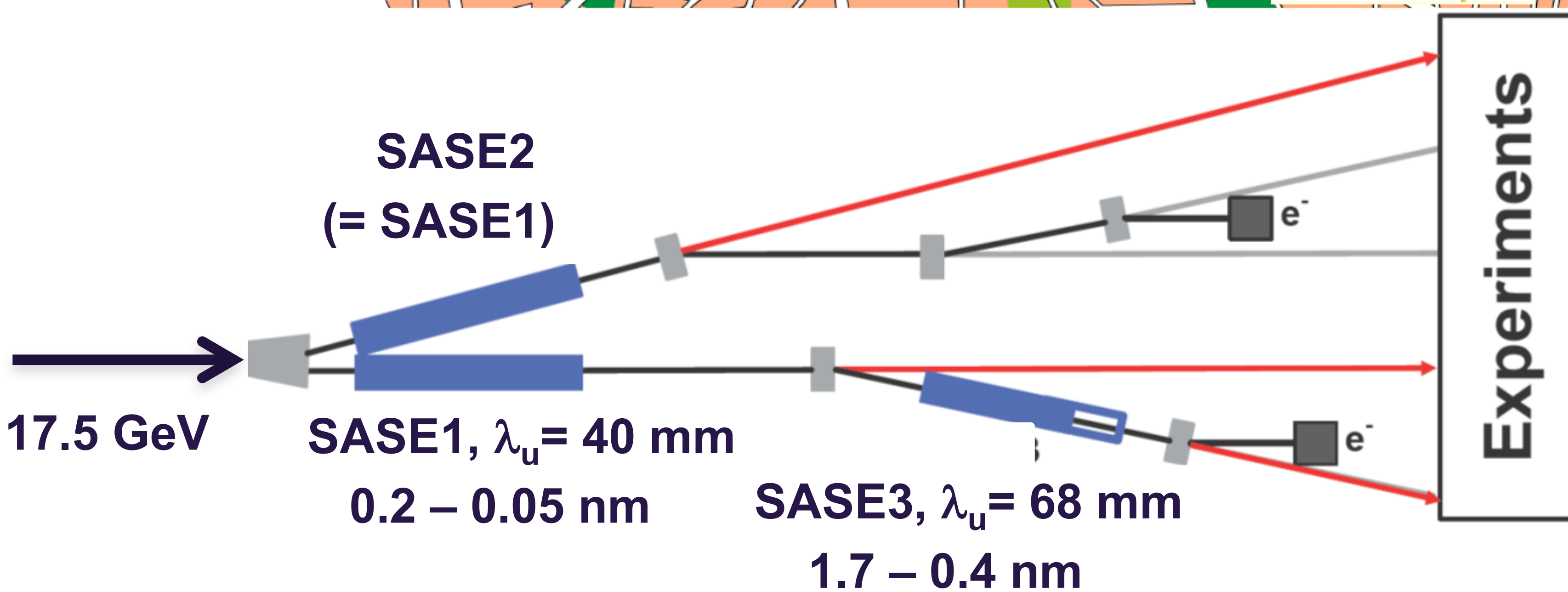
10 Hz rep. rate

1.4 ms RF pulse (750 us+650 us)

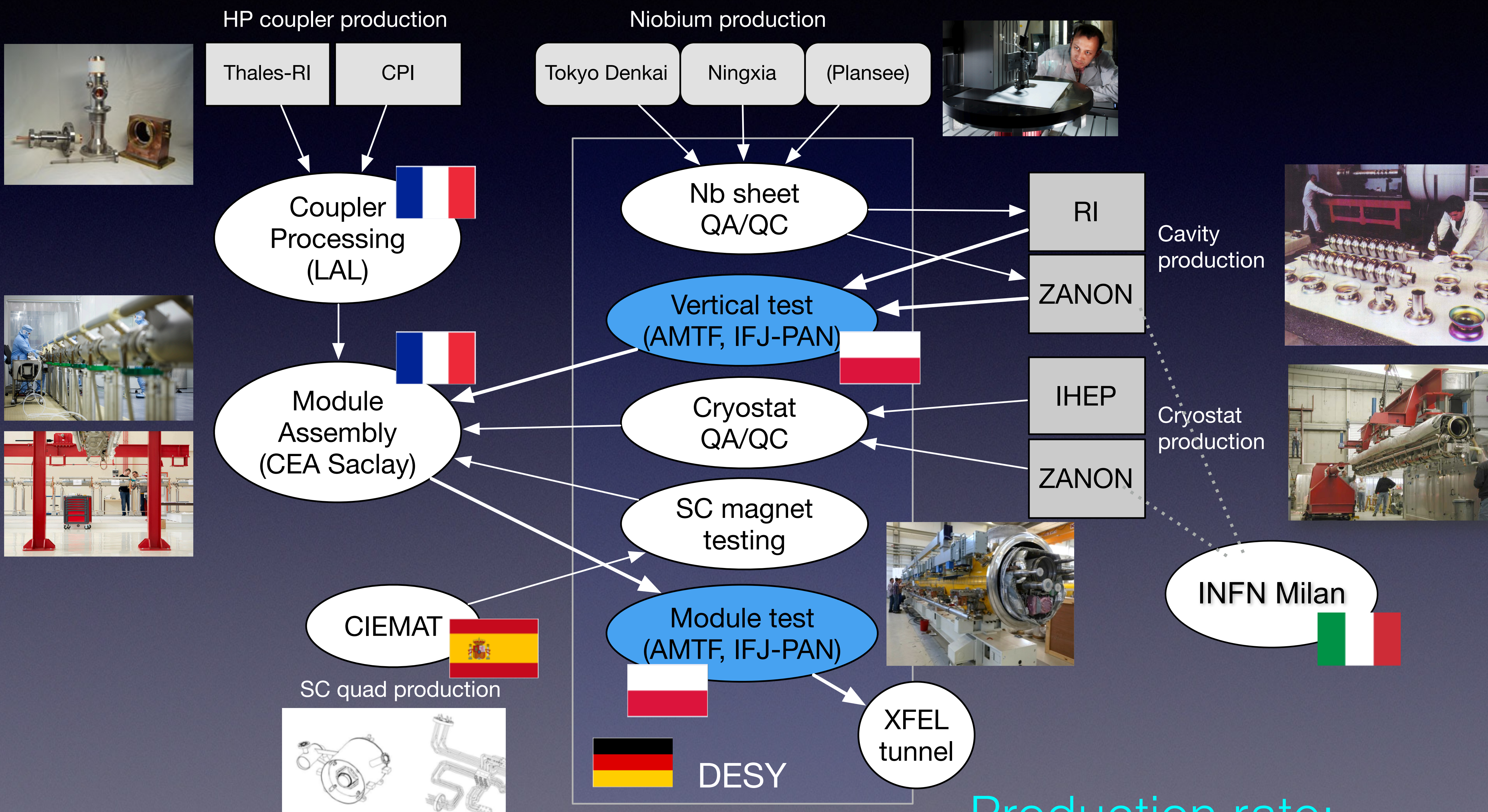
The European XFEL
Built by Research Institutes from 12 European Nations

Some specifications

- Photon energy 0.3 - 24 keV
- Pulse duration ~ 10 - 100 fs
- Pulse energy few mJ
- Superconducting linac 17.5 GeV
- 10 Hz (27 000 b/s)
- 5 beam lines / 10 instruments
  - Start version with 3 beam lines and 6 instruments
- Several extensions possible:
  - More undulators
  - More instruments
  - …….
  - Variable polarization
  - Self-Seeding
  - CW operation



XFEL cryomodule production



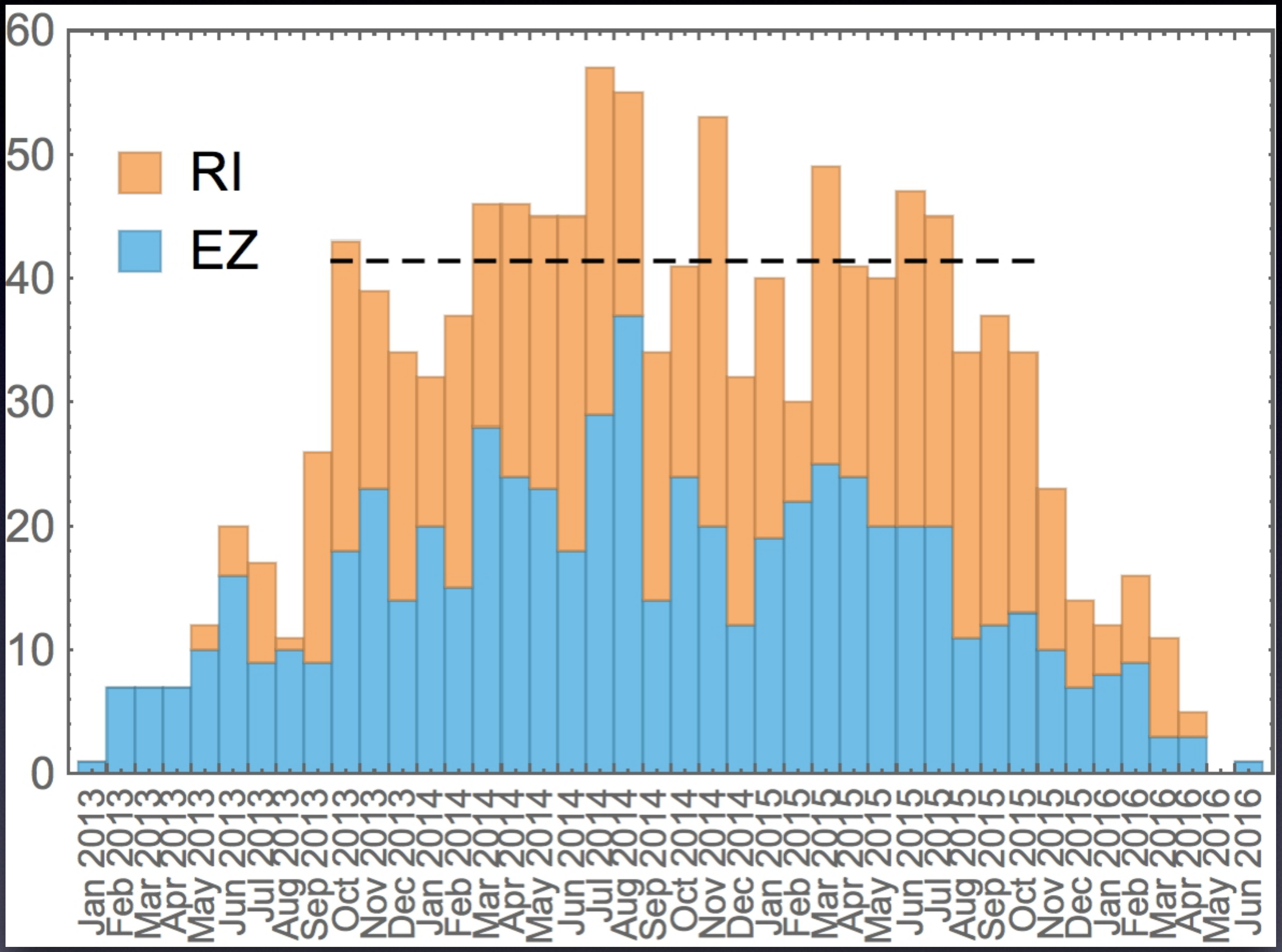
Production rate:
1 cryomodule per week

Achieving testing rates

Operated by staff from IFJ-PAN (Cracow)

- AMTF @ DESY
  - Accelerator Module Test Facility
  - Purpose build infrastructure
- Vertical cavity testing
  - Two independent cryostats
  - six inserts, each carrying 4 cavities
  - Test cycle ~3 days
- Module testing
  - Three parallel test benches
  - Module test 21→14 days
    - including cool down and warm up.

Achieving testing rates



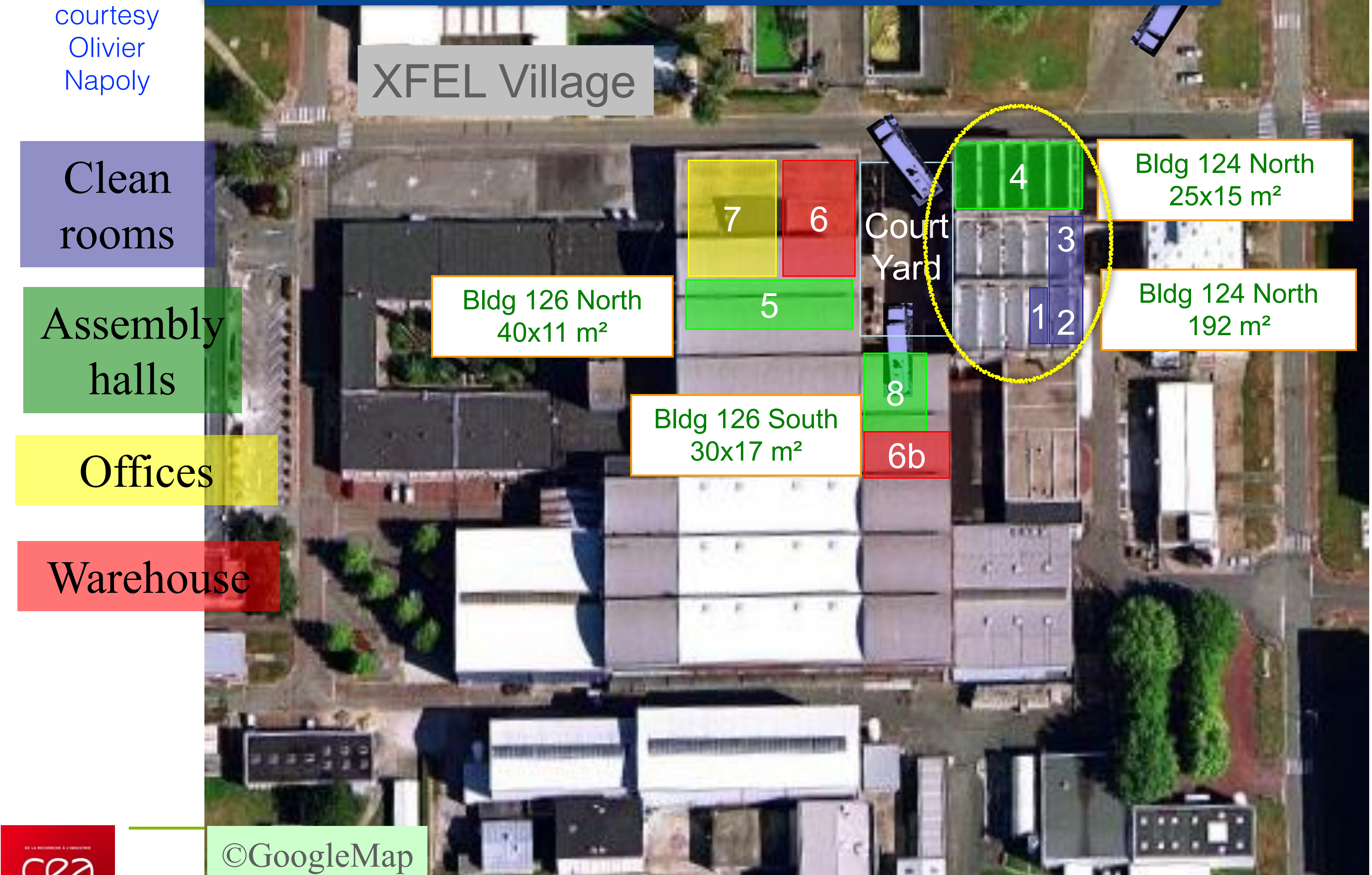
Two independent vertical cryostats

Six inserts, each taking 4 cavities

Average rate during main production period ~10 cavity tests per week
Up to 15 peak achieved

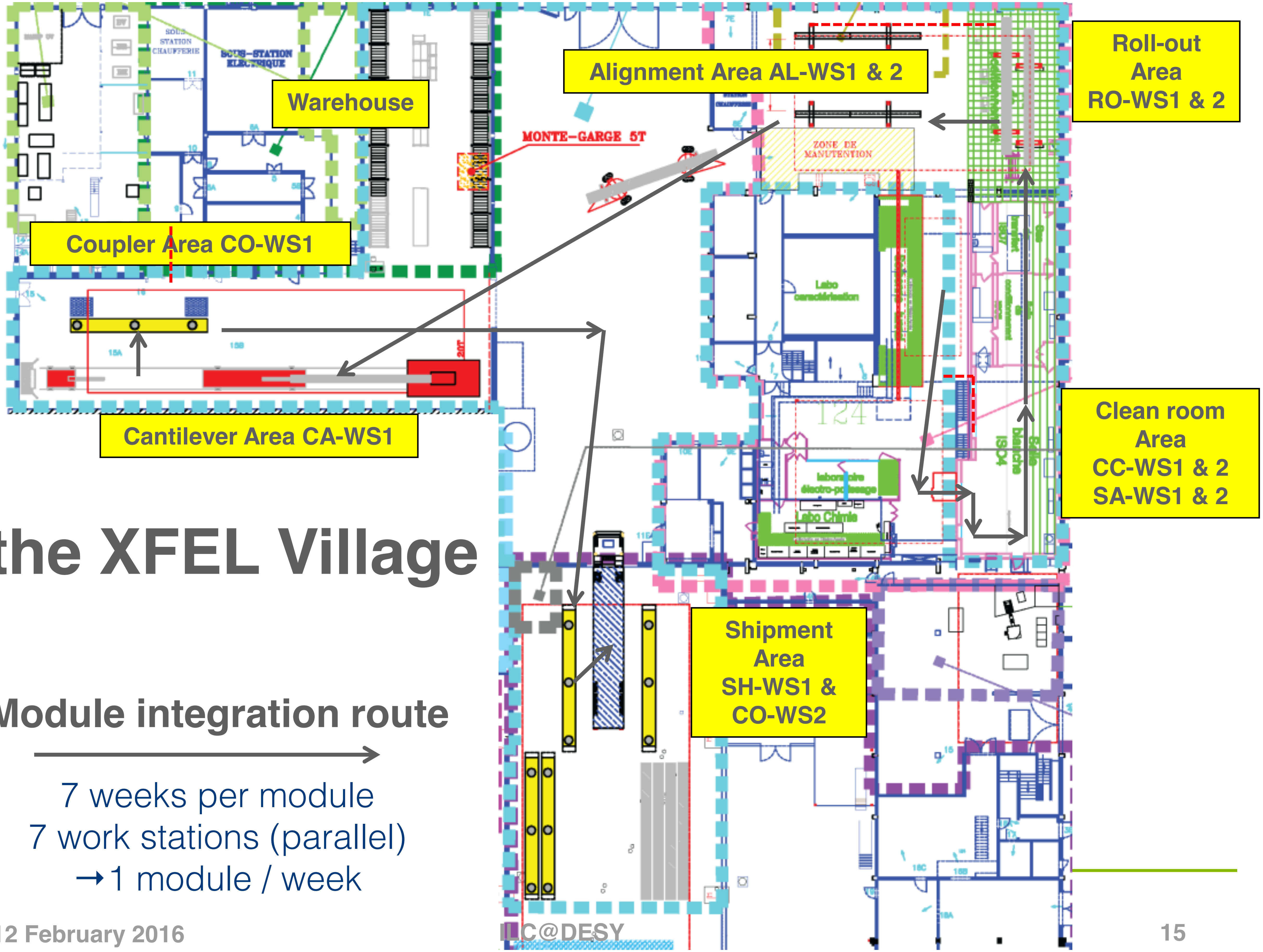
Module Assembly Facility at CEA Saclay (2300 m²)

courtesy Olivier Napoly



Assembly Hall : Workstations

courtesy Olivier Napoly



the XFEL Village

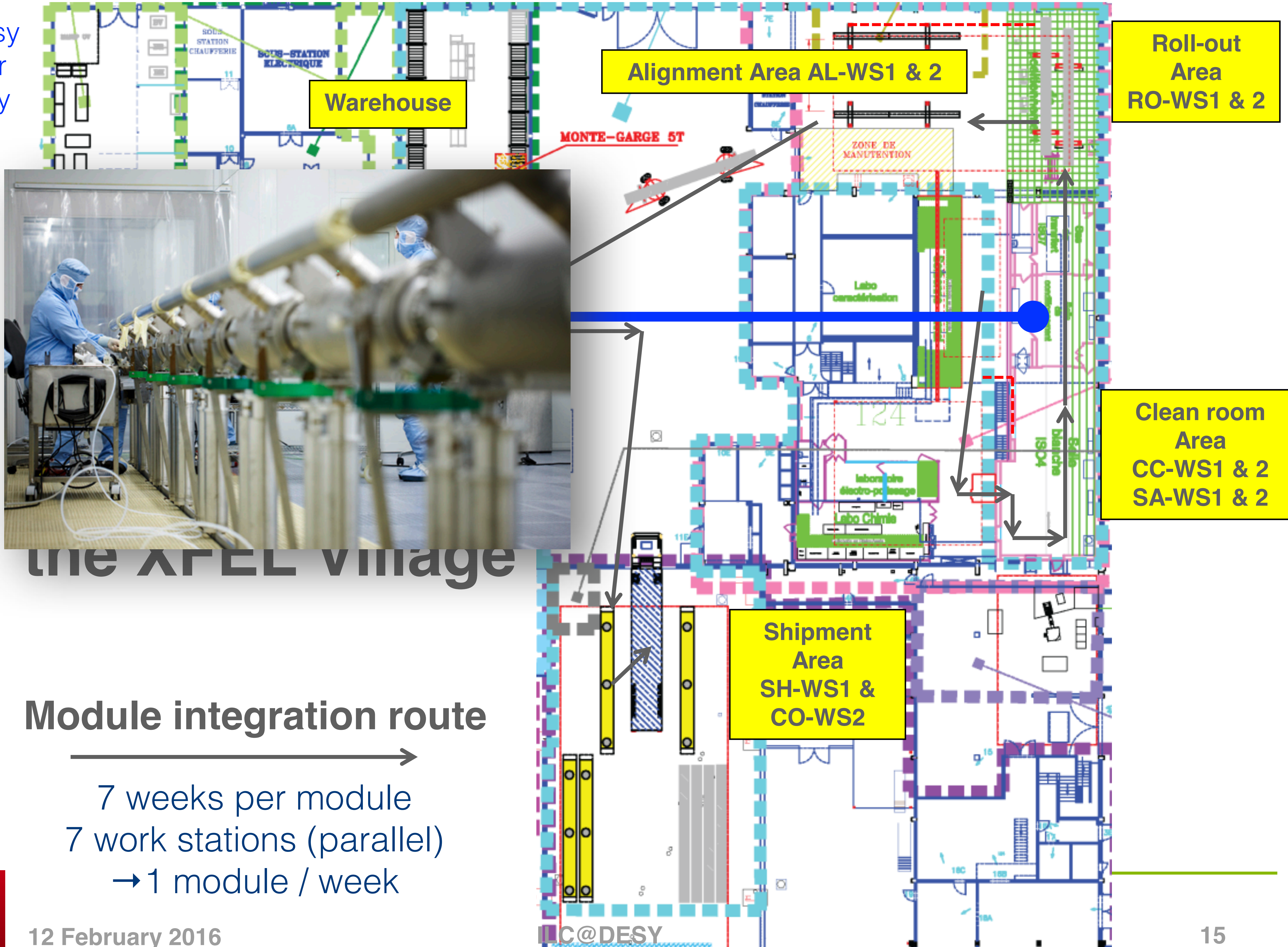
Module integration route

→

7 weeks per module
7 work stations (parallel)
→1 module / week

Assembly Hall : Workstations

courtesy Olivier Napoly



Module integration route

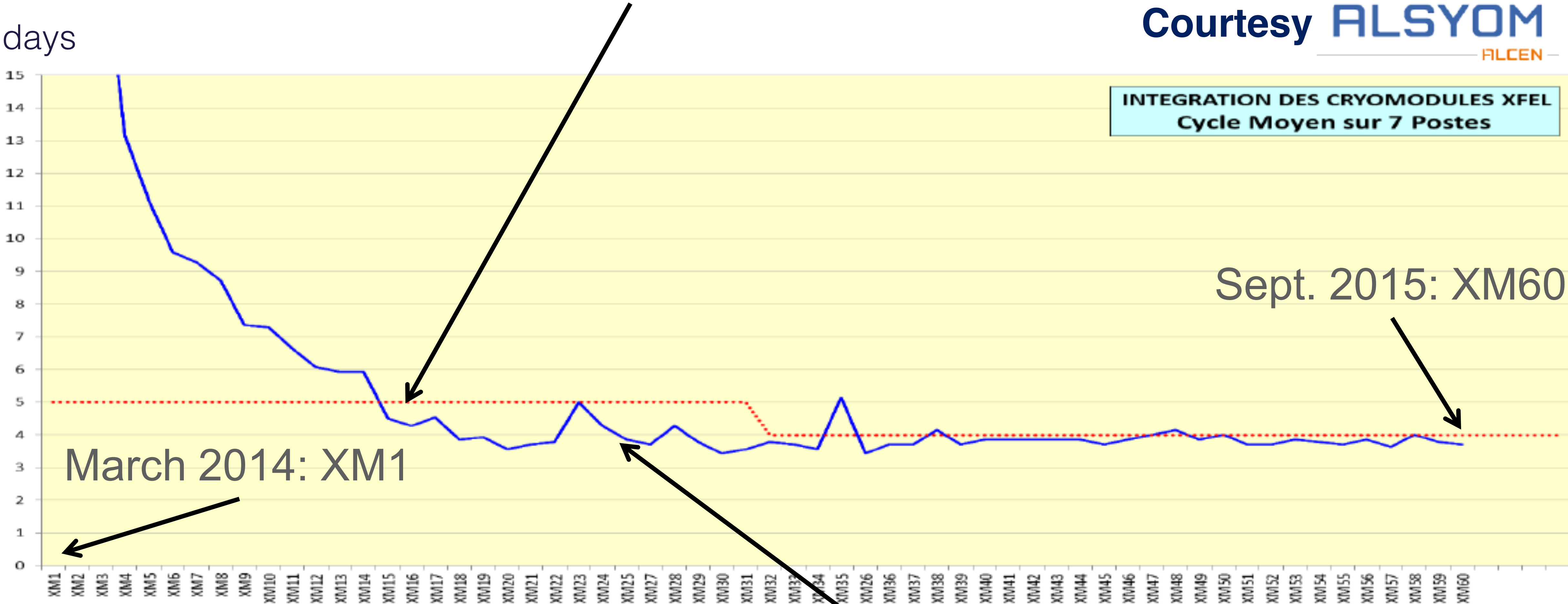
→

7 weeks per module
7 work stations (parallel)
→1 module / week

Module assembly rate

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

Courtesy ALSYOM ALCEN



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

This 'accelerated' rate is needed to close the XFEL tunnel mid-2016:

- XM80 to be delivered at the end of December 2015
- XM100 to be delivered at the end of April 2016

courtesy Olivier Napoly

XFEL performance results

So how well did we do?

- gradient
- Q_0

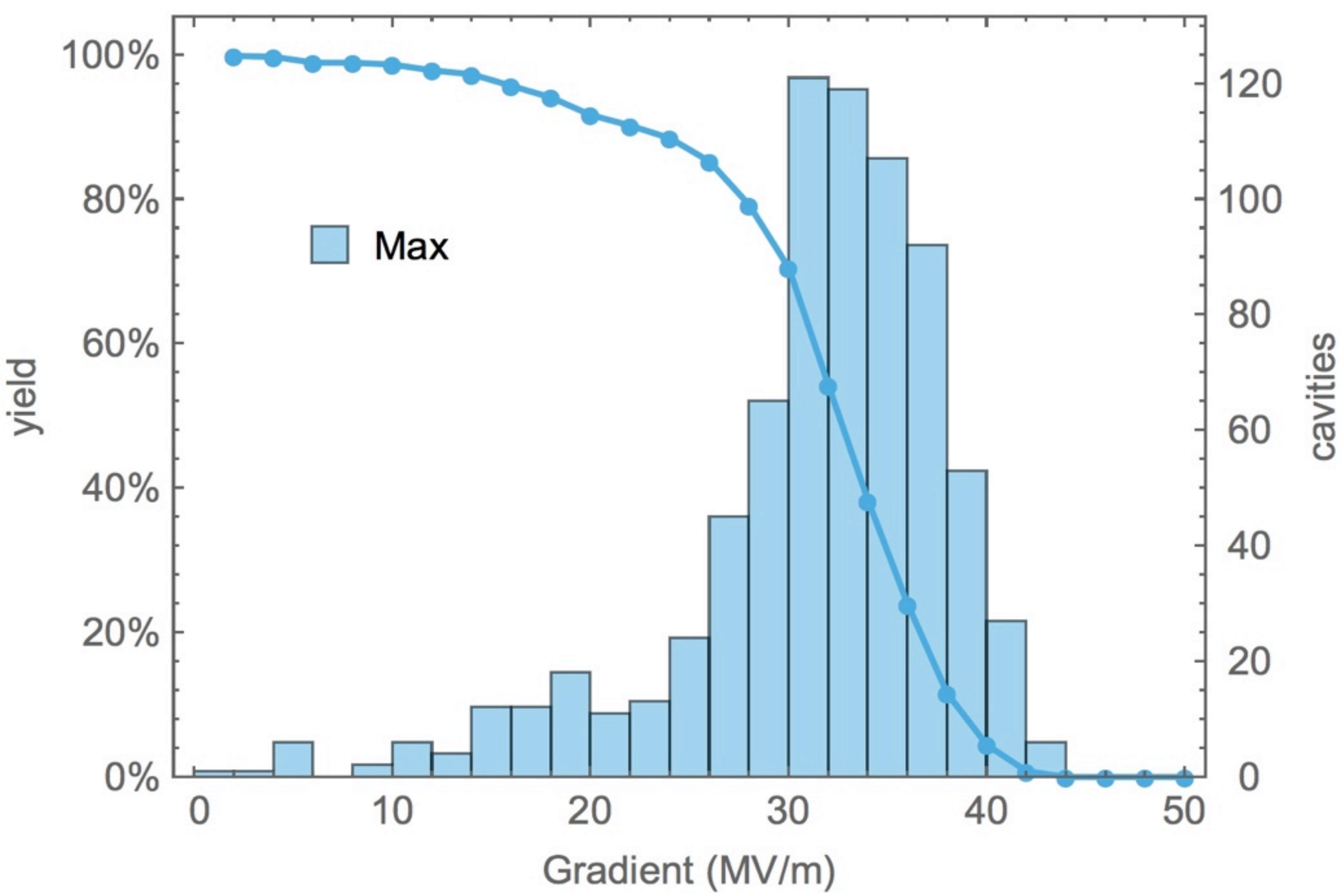
- Cavity vertical test (vendor acceptance test)
- Module performance test

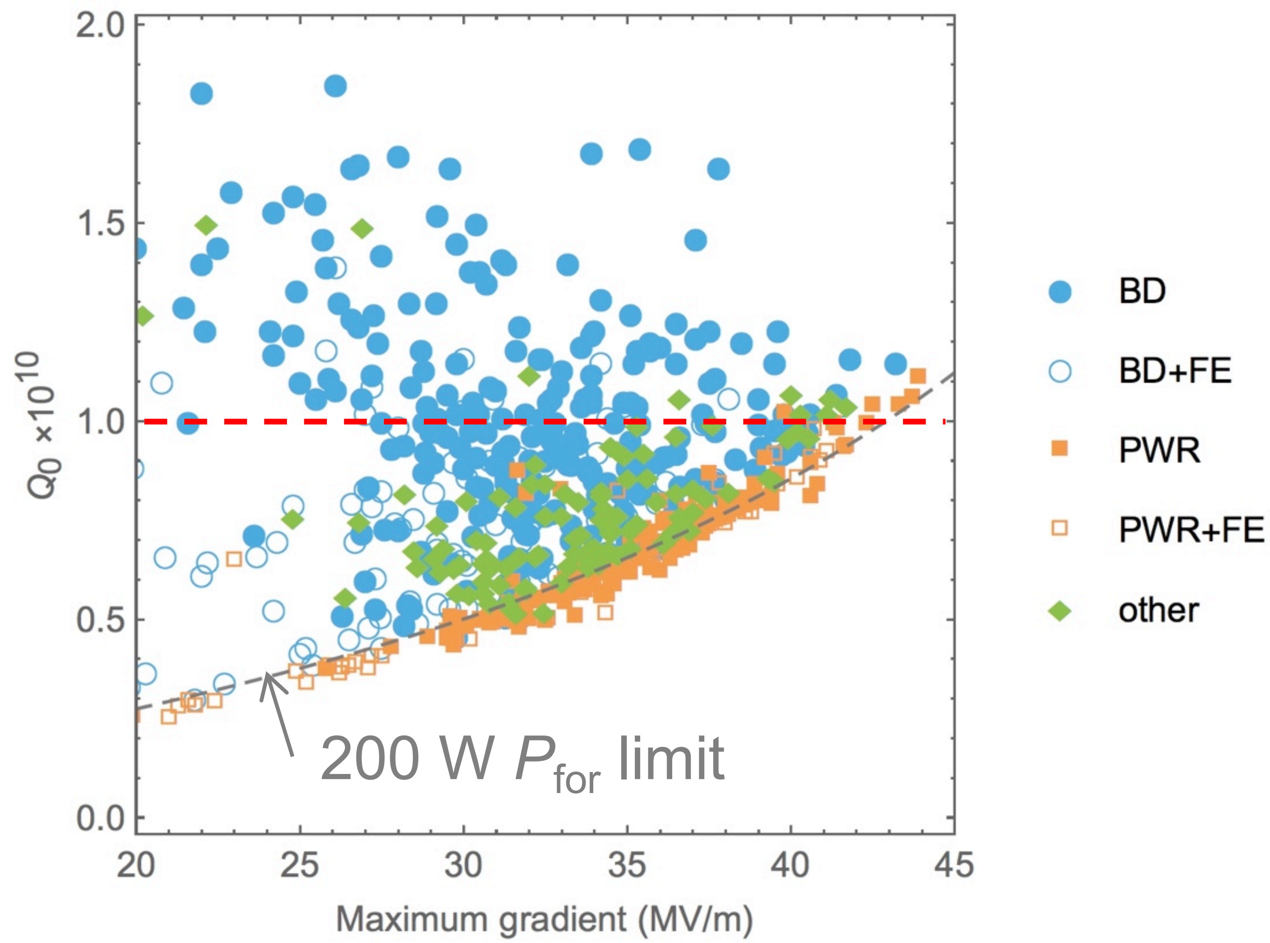
European XFEL

As Received Maximum Gradient in the VT

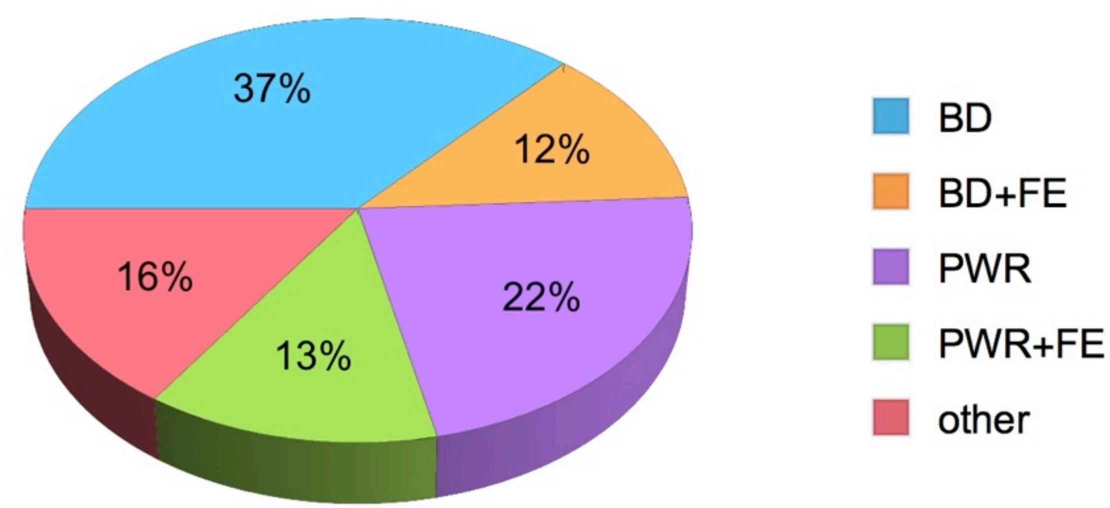
typical individual error: 10%

BD: breakdown (quench) - FE: field emission - PWR: power limited





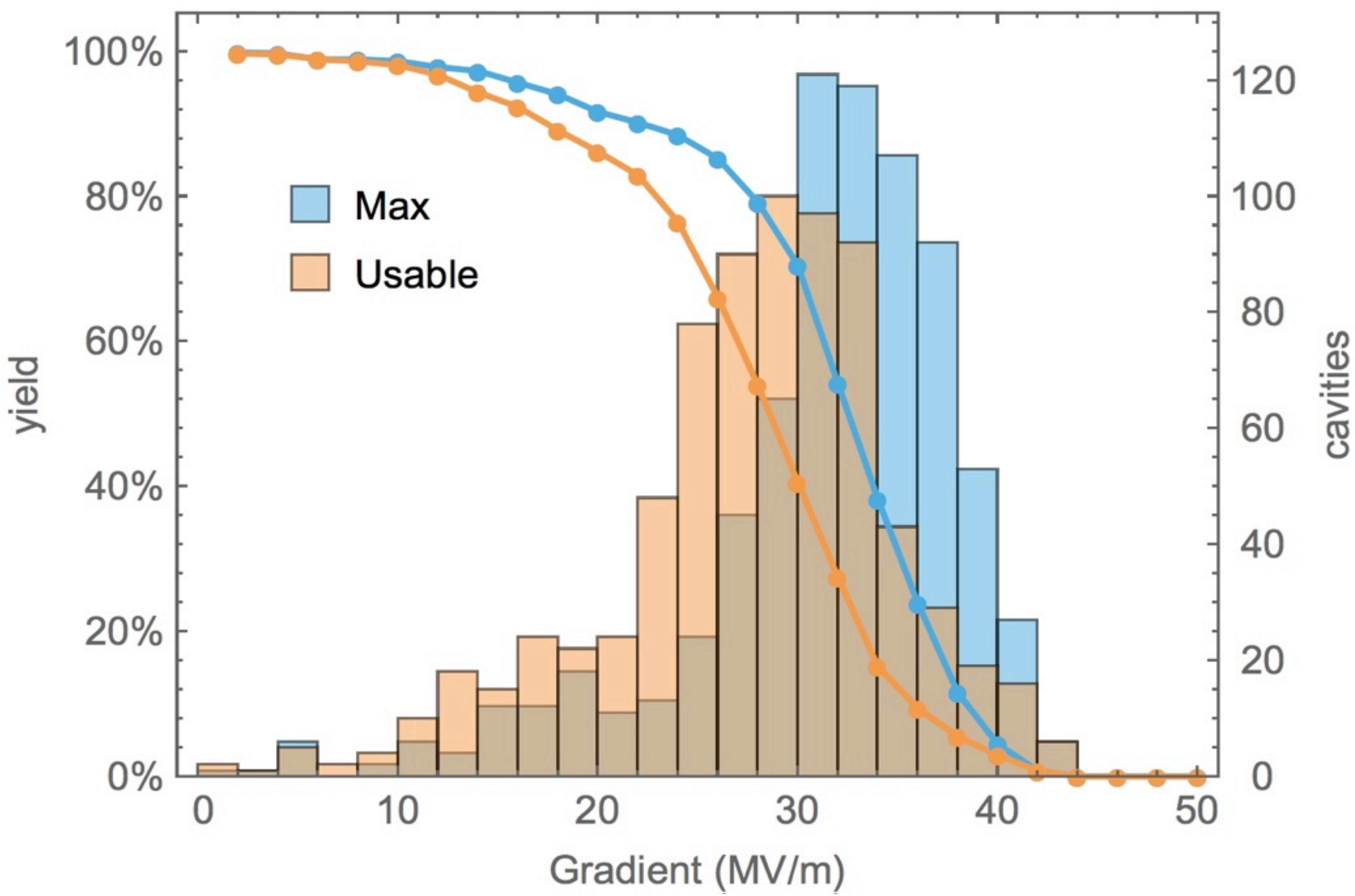
		Max
Average	MV/m	31.4
RMS	MV/m	6.8
Median (50%)	MV/m	32.5
Yield ≥20 MV/m		92%
Yield ≥26 MV/m		85%



INFN
DESY
HELMHOLTZ ASSOCIATION

As Received Usable Gradient in the VT

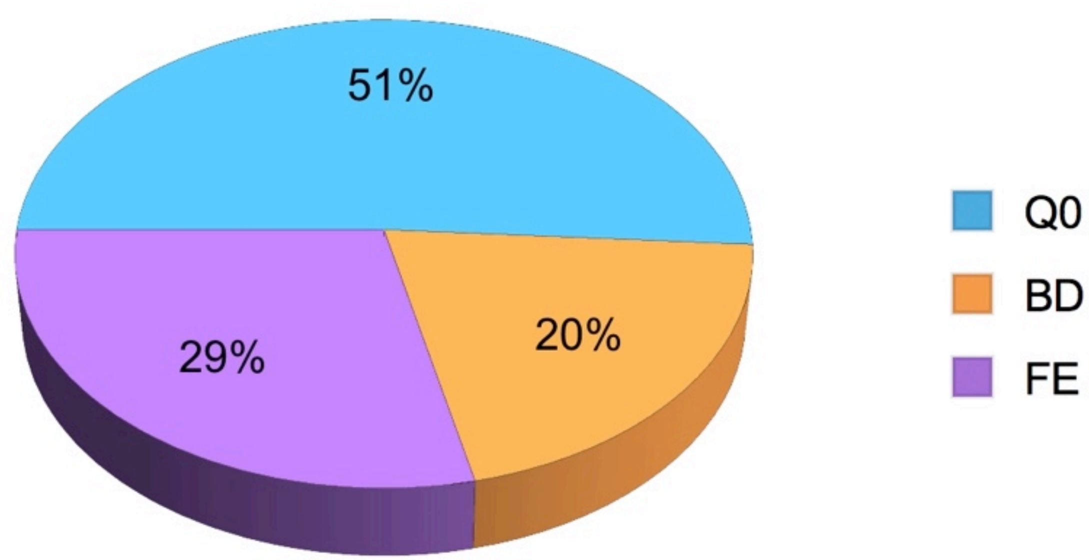
typical individual error: 10%



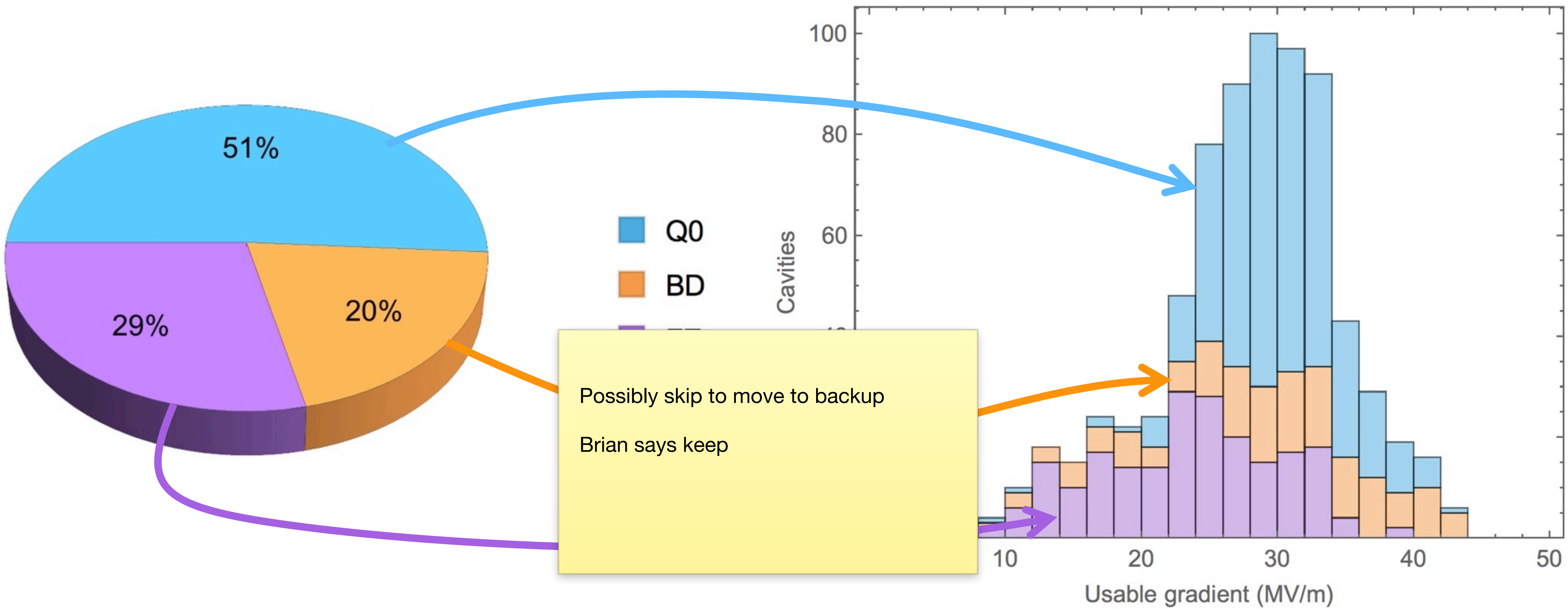
		Max	Usable
Average	MV/m	31.4	27.7
RMS	MV/m	6.8	7.2
Median (50%)	MV/m	32.5	28.7
Yield ≥20 MV/m		92%	86%
Yield ≥26 MV/m		85%	66%

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

→ Usable Gradient



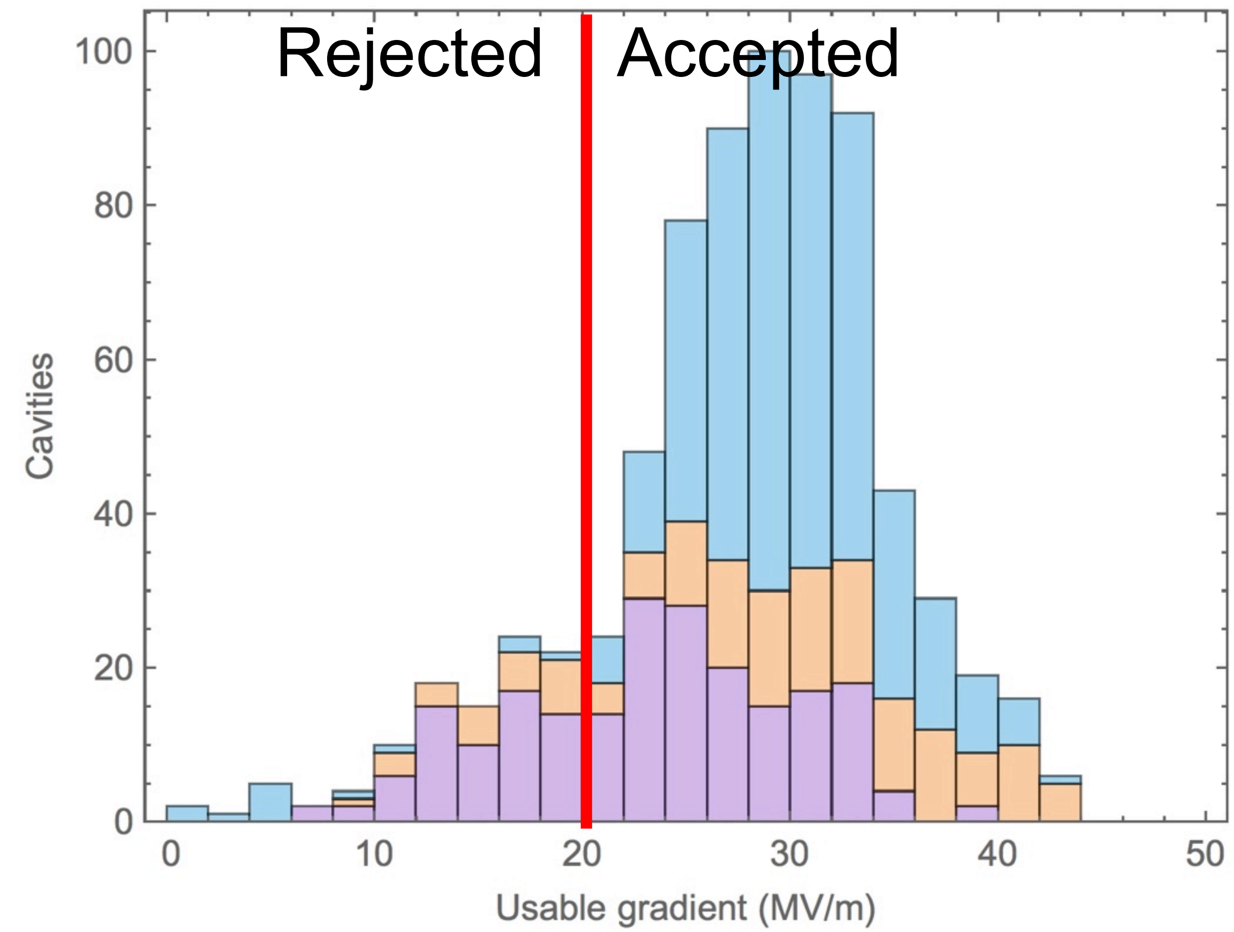
Usable gradient: limiting effects

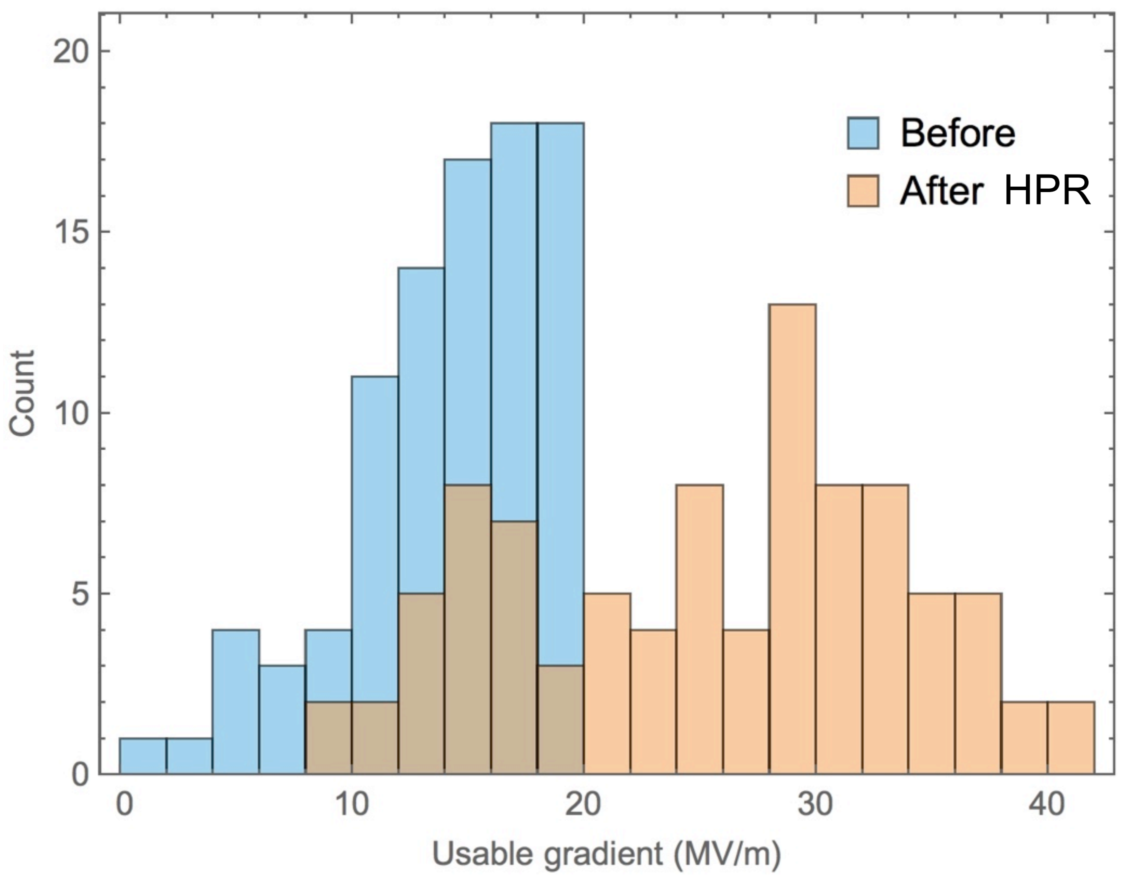


- Q_0 dominates at higher gradients (high-gradient Q-slope)
- Field Emission (FE) dominates <24 MV/m
- Quench (BD) not dominant –mostly higher gradients

Recovering low performance cavities

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





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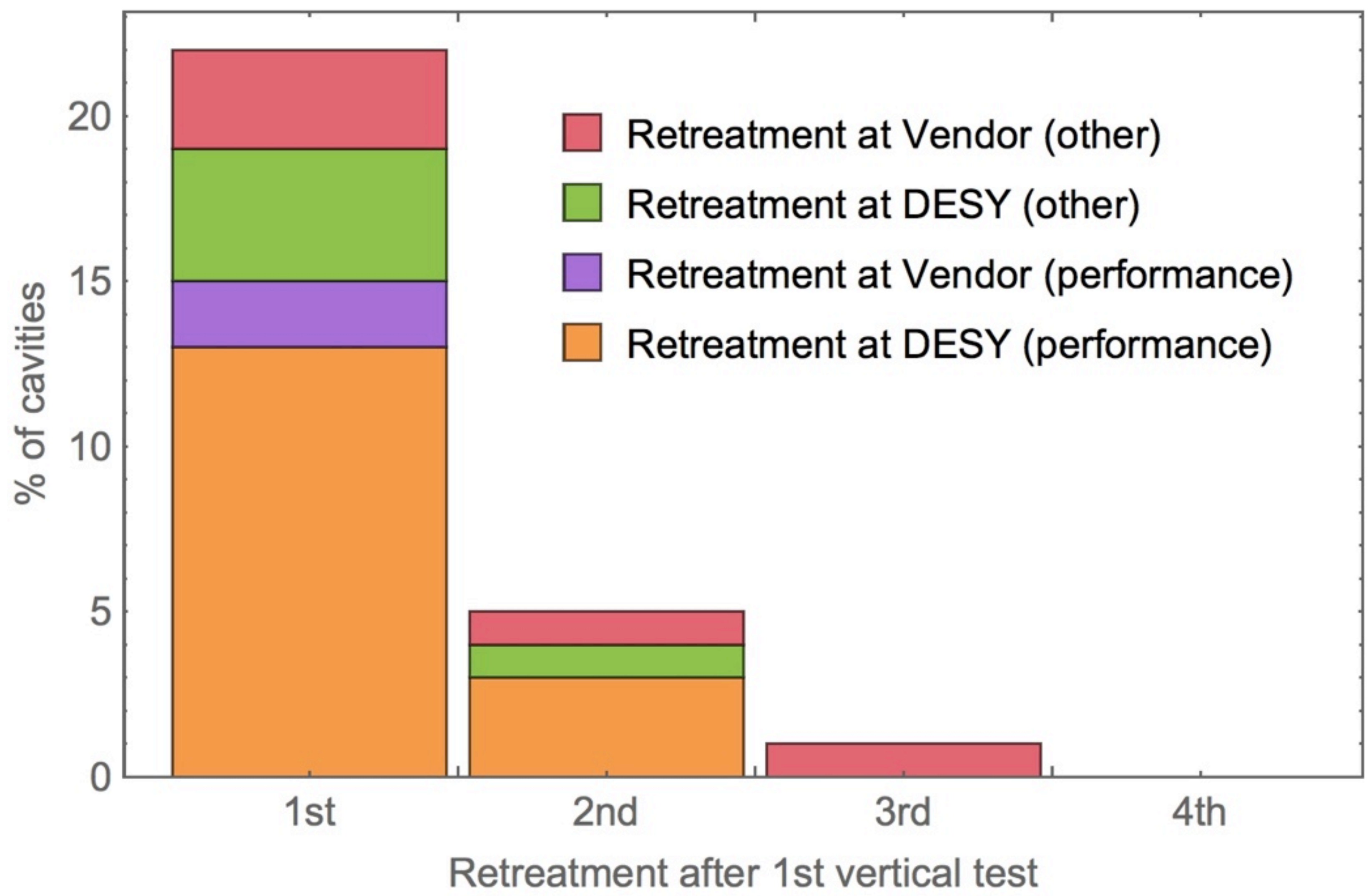
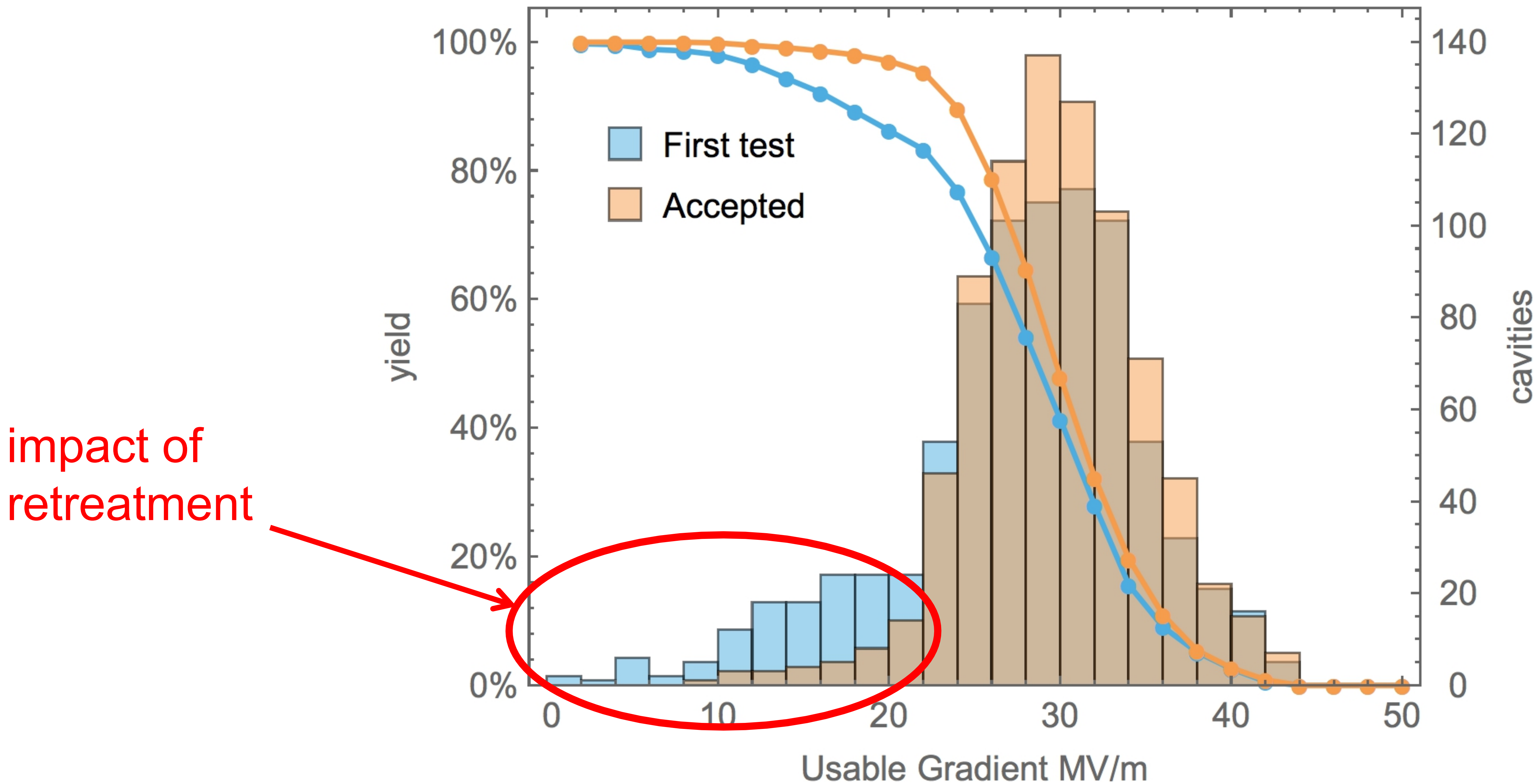
Number of retreatments after the 1st vertical test

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



Final performance (sent for module assembly)

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



Cryomodule assembly at CEA Saclay

Always a risk when cavity vacuum is broken
(even in the clean room)

Comparing VT with module test performance

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

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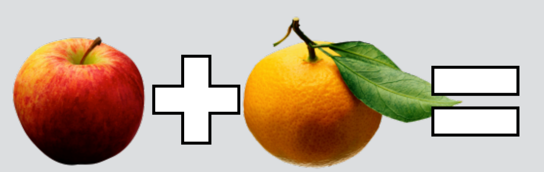
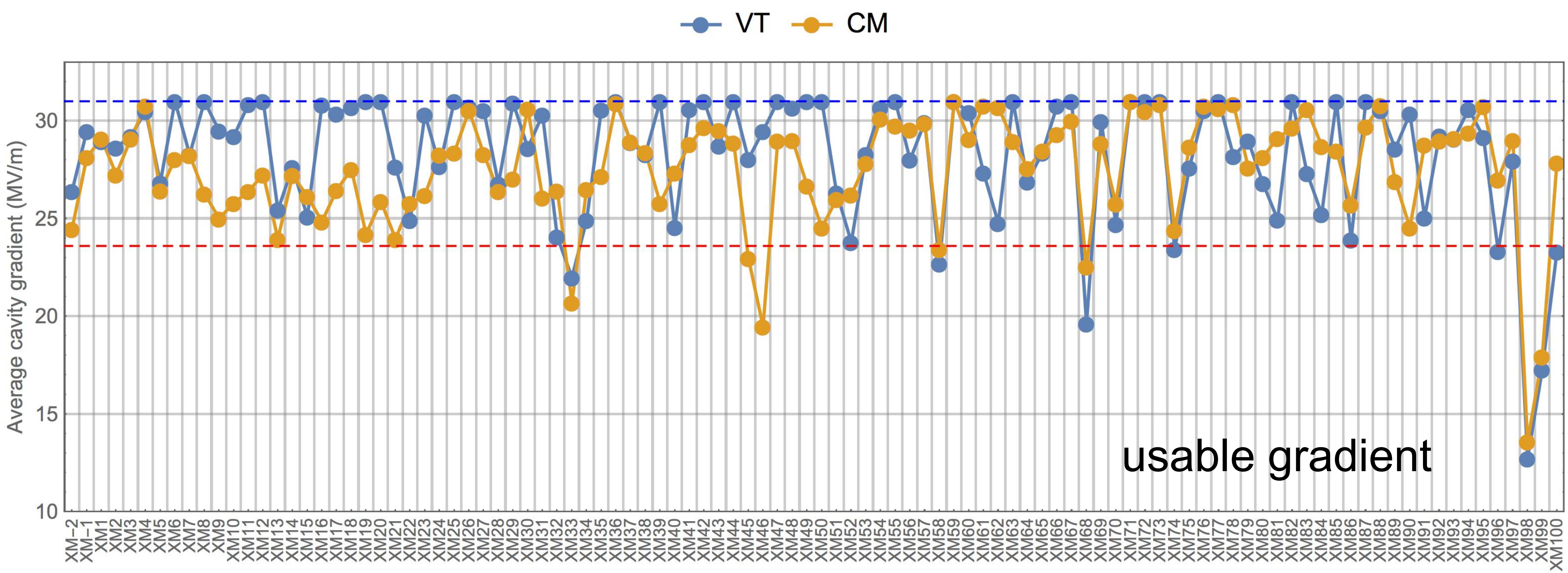
	VT	MT	
Maximum gradient	No administrative limit	limited to 31 MV/m	*True impact unknown (but can set an upper limit)*
Field Emission (X-Ray)	Two monitors above and below cryostat	Two monitors upstream and	*Different geometry / calibration makes ...t comparison ...ult*
Q_0	[illegible]	[illegible] measurement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

when making comparisons,  ?

Cryomodule average gradient performance



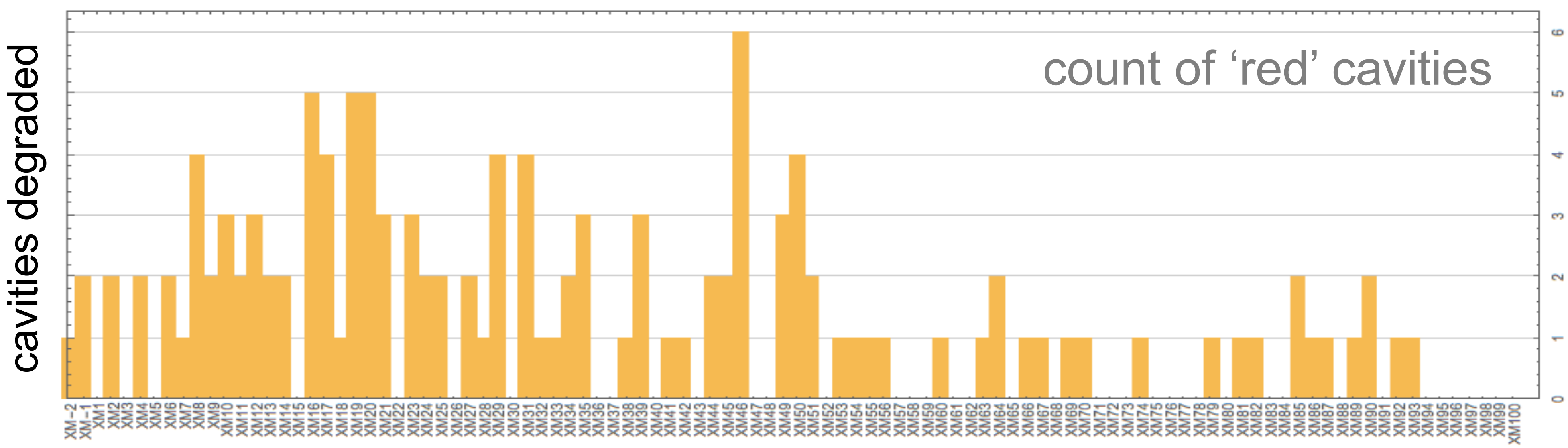
VT capped at 31 MV/m for fair comparison

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

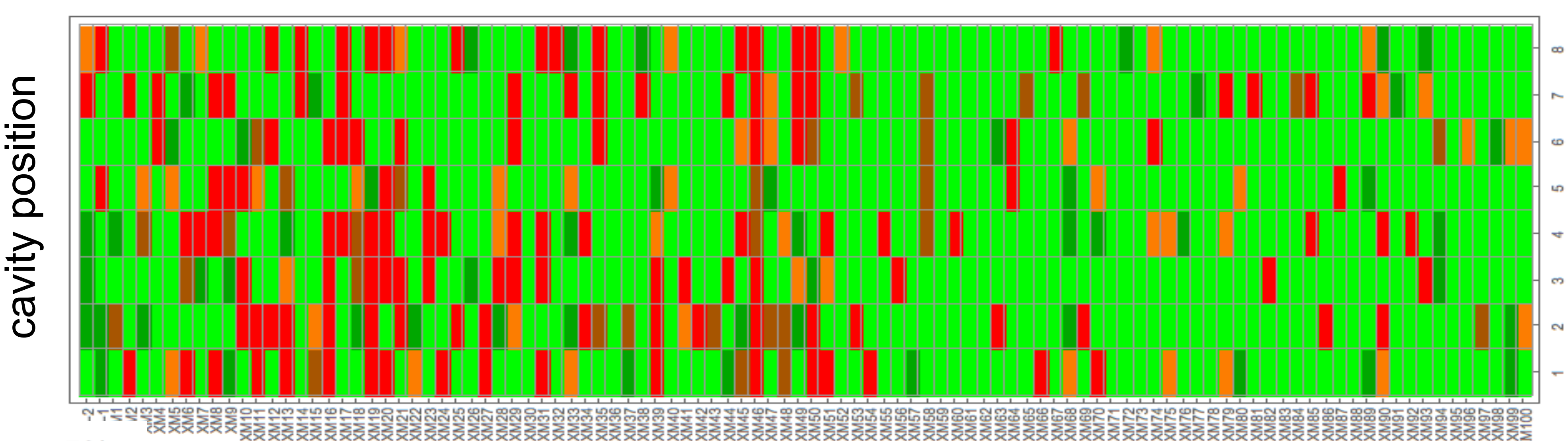
~3% difference measured this way

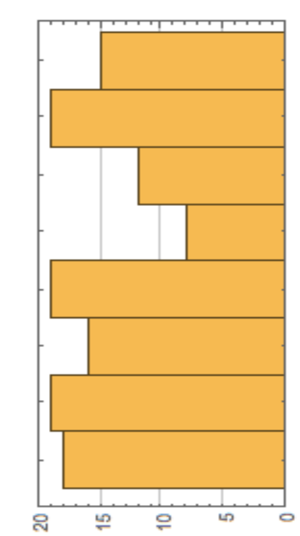
Degradation matrix

Degradation defined as ≥20% (red)



best place to be a happy cavity in a cryomodule



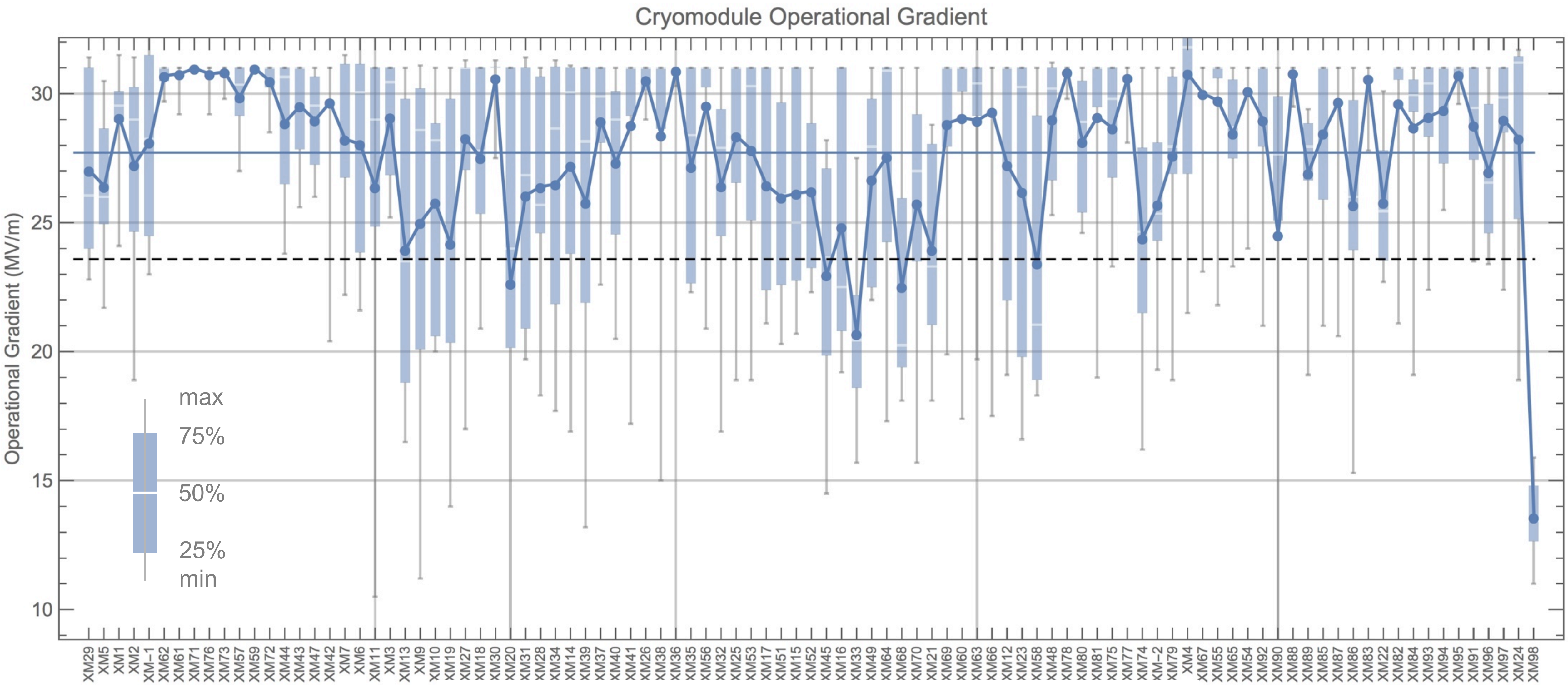


cavities degraded

cryomodule number

- <5%
- <10%
- <15%
- <20%
- ≥20%

Cryomodule performance (AMTF module test)

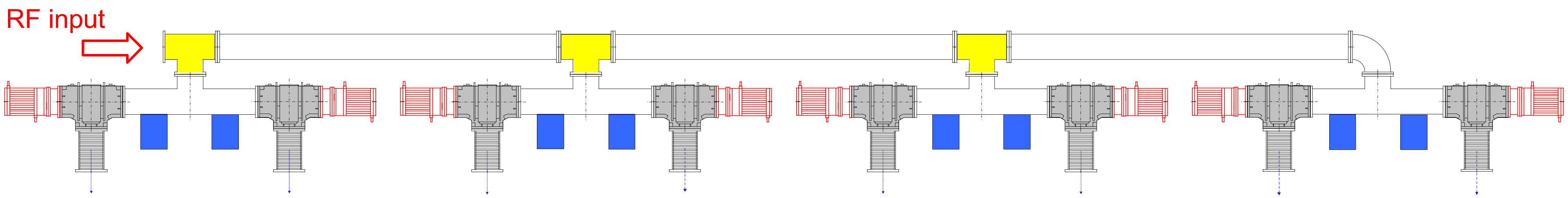


cryomodules installed in linac

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

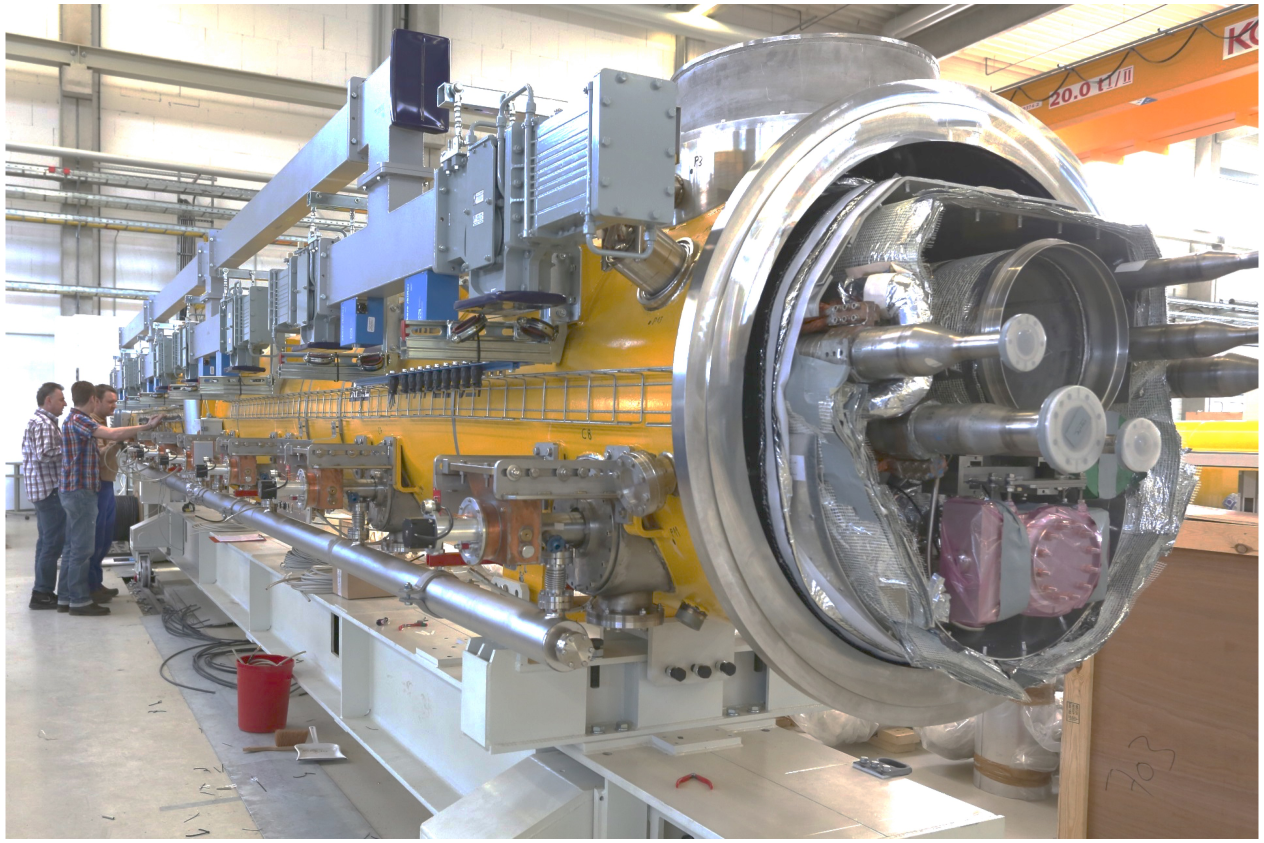
→ “Fine tuning” of waveguide distribution to maximise energy gain.

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



courtesy V. Katelev

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



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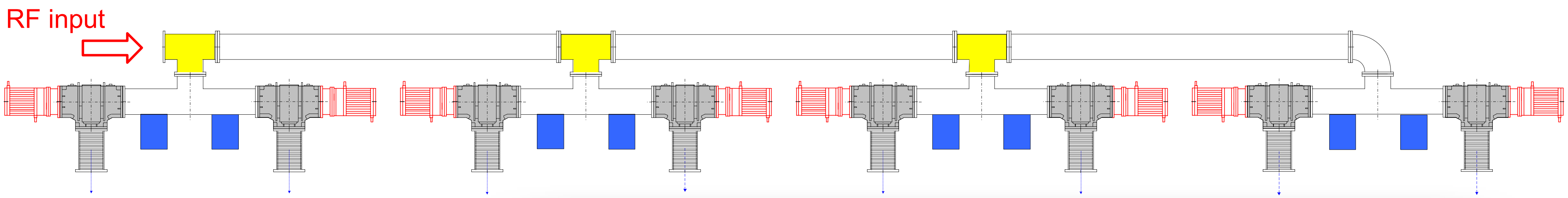

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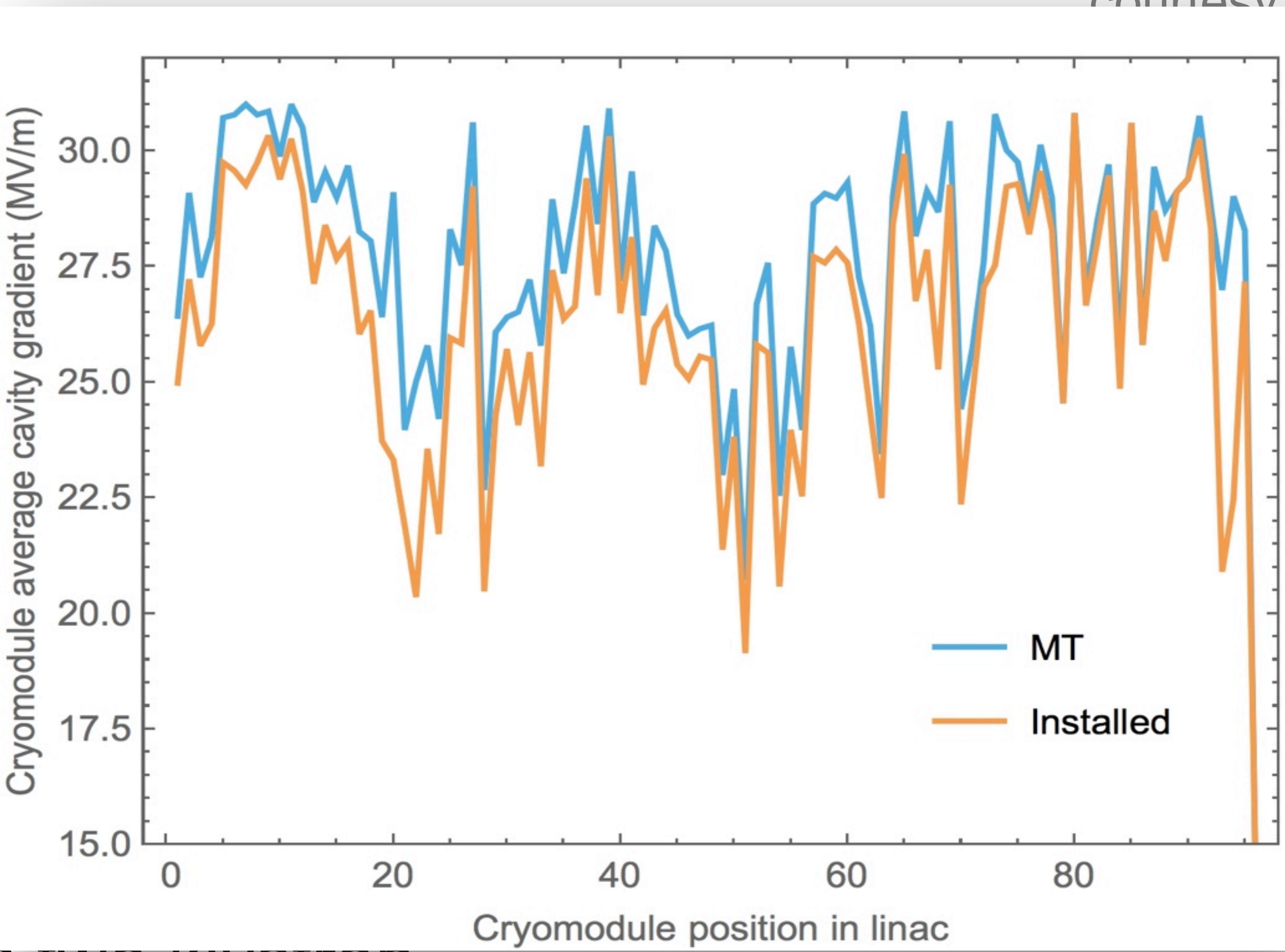

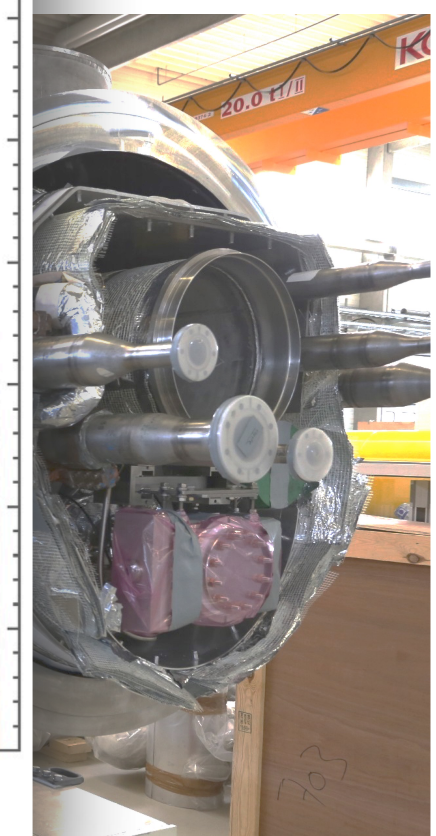

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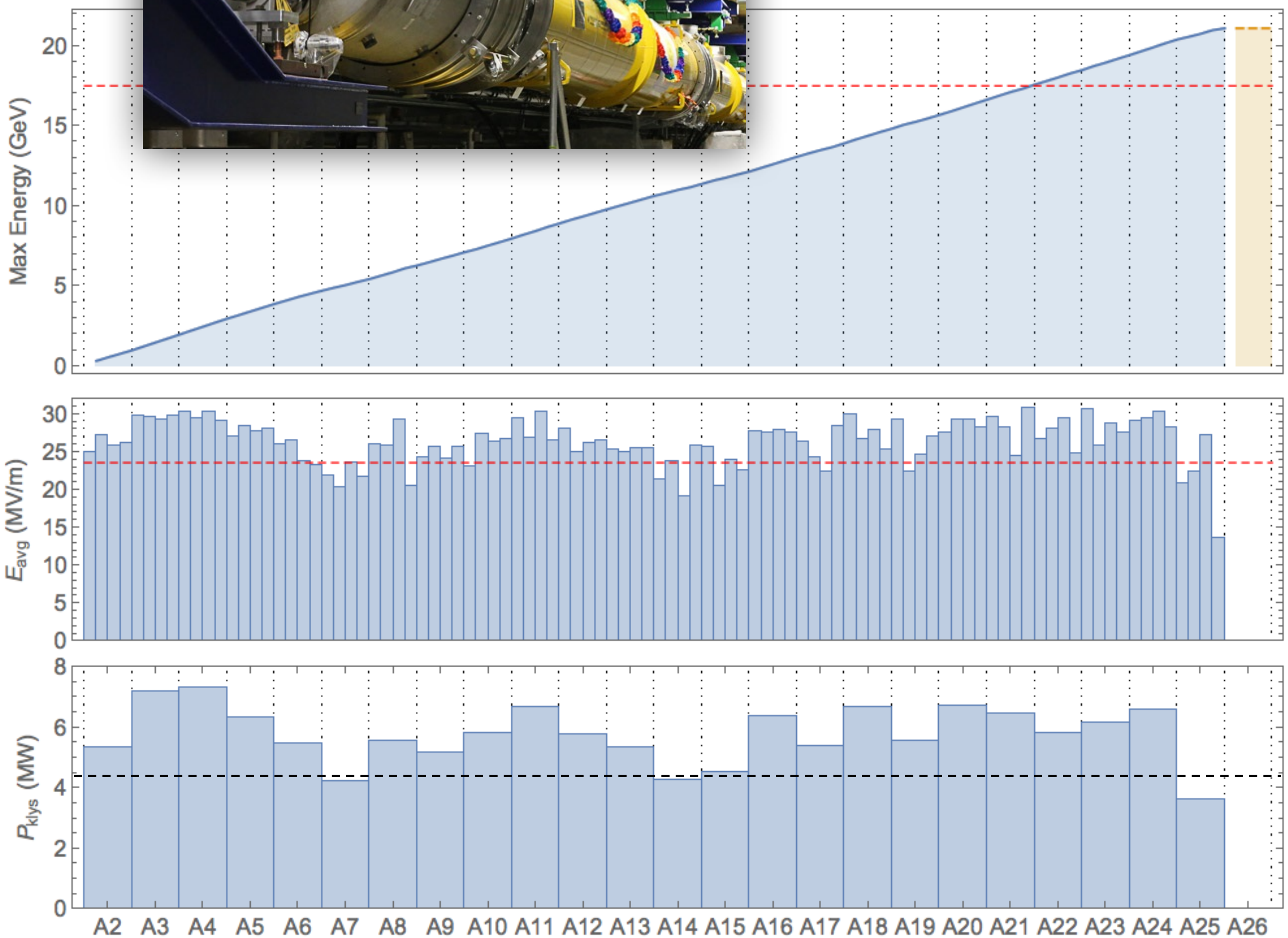
  results
  - maximising voltage
  - up to 3dB difference b
    cavity pairs
- Allow up to 3dB split bet
  adjacent cryomodule pa
- Equal power output from two klystron
  arms

see THPLR067 Choroba, Katalev, Apostolov

Projected installed energy profile

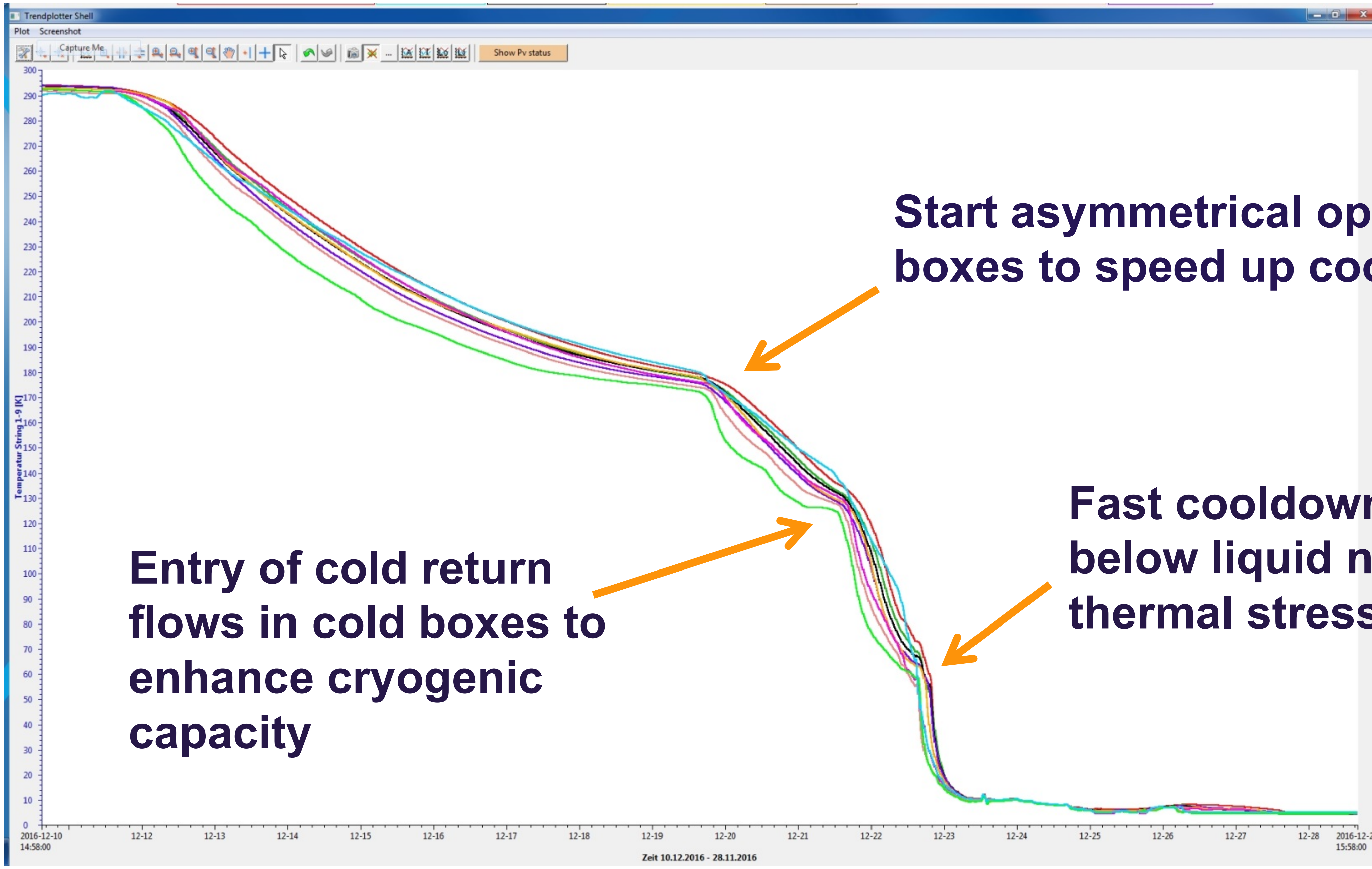


E_{max} ~ 20 GeV

14% margin at 17.5 GeV

last RF station not installed (4 cryomodules)

First Cooldown of XFEL Linac (300K to 4K)



Start asymmetrical operation of two cold boxes to speed up cooldown

Entry of cold return flows in cold boxes to enhance cryogenic capacity

Fast cooldown at temperatures below liquid nitrogen (no more thermal stress)

10.12.2016

24.12.2016

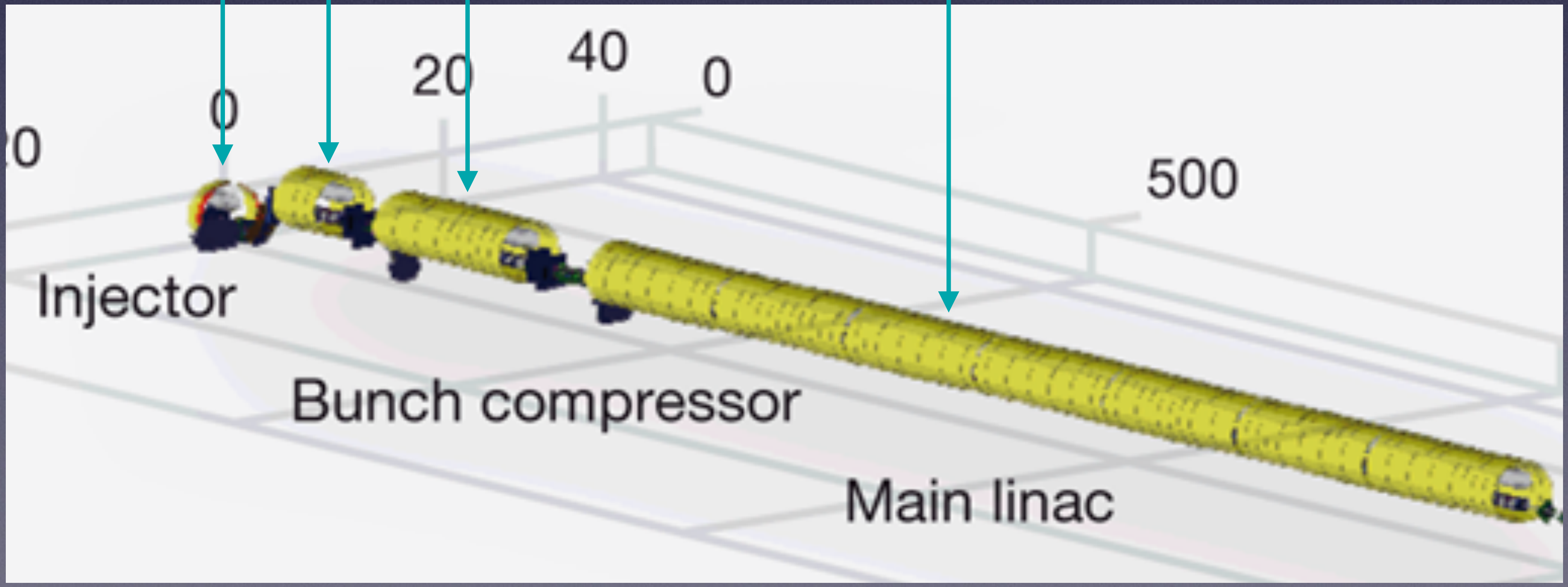
- **No Cold Leaks!!!**

XFEL cryogenics

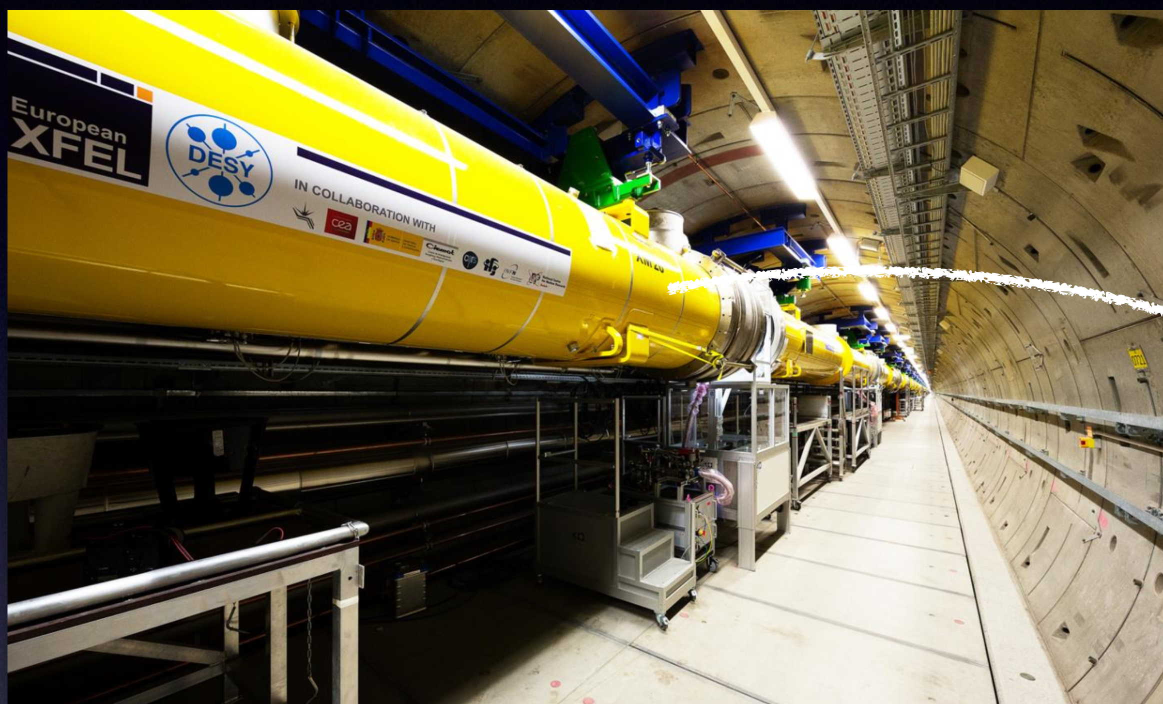
- 2K operation achieved on 6.01.2017 (P = 30.6 mbar)
- He pressure stability ±0.3% (spec. ±1%)
- Still “learning” new Cold Compressors (CC)
  - Not yet operating at design capacity
  - Reliability issues
- Operations issues
  - relatively high ‘dynamic load’ (RF - scales as G^2)
    - commissioning at 1 Hz to keep dynamic load low
    - Not yet “challenged”

XFEL commissioning

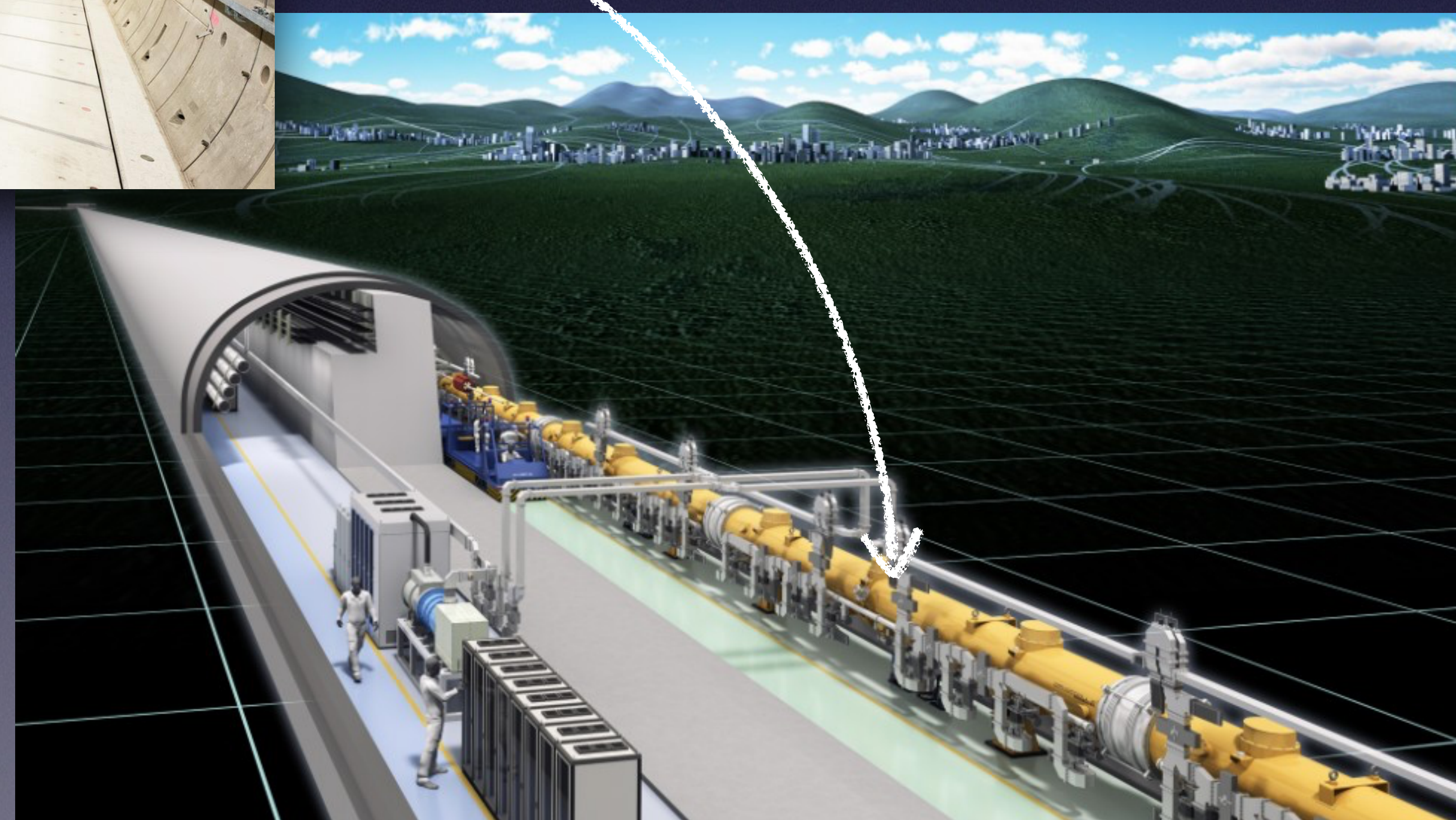
- Injector commissioning (130 MeV) 12.2016 ✔
    - L1 (A2) commissioning (600 MeV) 01.02.2016 ✔
        - L2 (A2/3/4) commissioning (2.4 GeV) 15.02.2016 ✔
            - L3 (A6-25) commissioning (→17.5 GeV) ongoing (sched. until 15.04.2017)



From XFEL to ILC?



So how close are we?



Gradient?
Cost??

ILC cavity specs

	ILC		XFEL (spec)	
	G (MV/m)	Q_0	G (MV/m)	Q_0
Vertical Test	35.0	5×10^9	26.0	10^{10}
Installed	31.5	10^{10}	23.6	10^{10}

ILC cavity specs

	ILC		XFEL (spec)	
	G (MV/m)	Q_0	G (MV/m)	Q_0
Vertical Test	35.0	5×10^9	26.0	10^{10}
Installed	31.5	10^{10}	23.6	10^{10}

ILC TDR assumed ±20% gradient spread ($28\leq G\leq 42$ MV/m)

	Yield ≥28 MV/m	$\langle G\rangle$ ≥28 MV/m
As received (1st pass)	75%	35 MV/m
After 25% retreated (2nd pass)	90%	35 MV/m

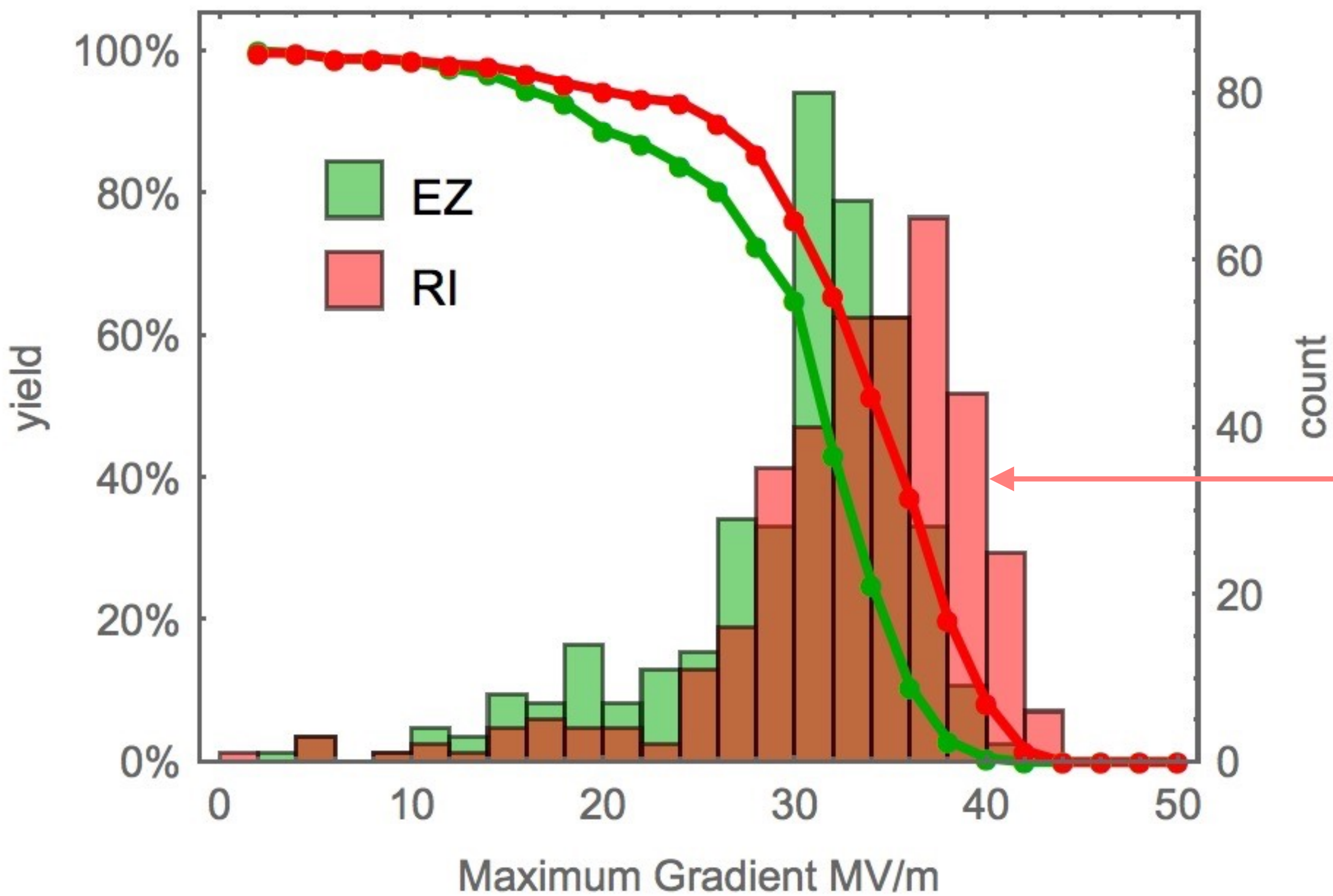
cost model

⇒1.25 VT per cavity

European XFEL

Test results by Vendor (MAX GRADIENT)

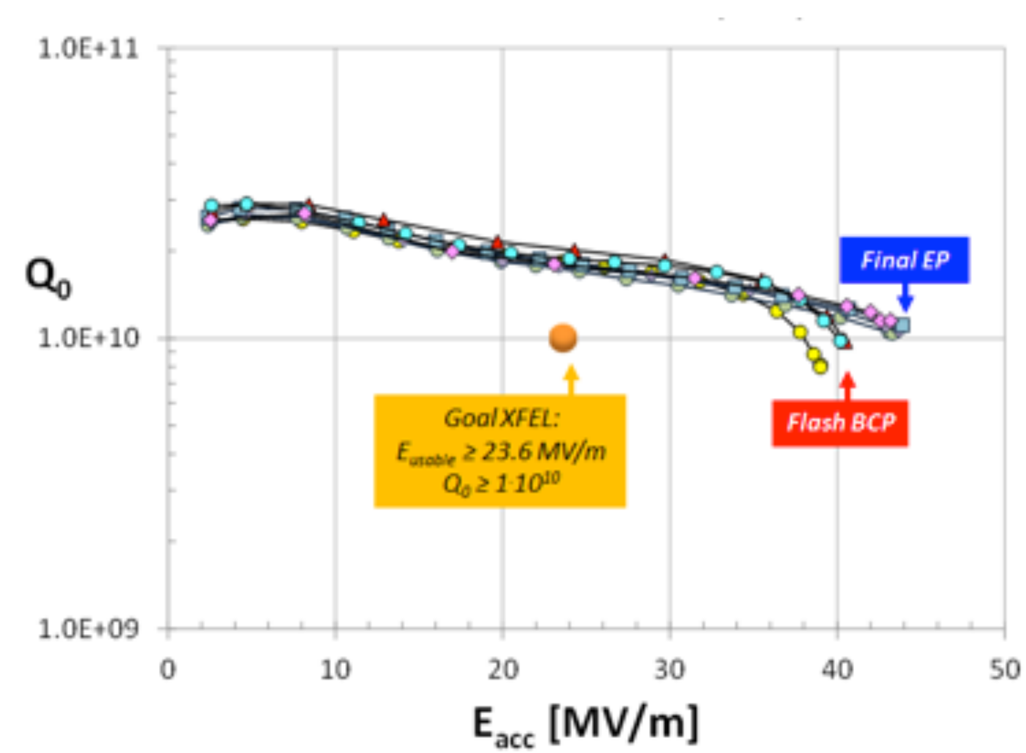
“As received” test



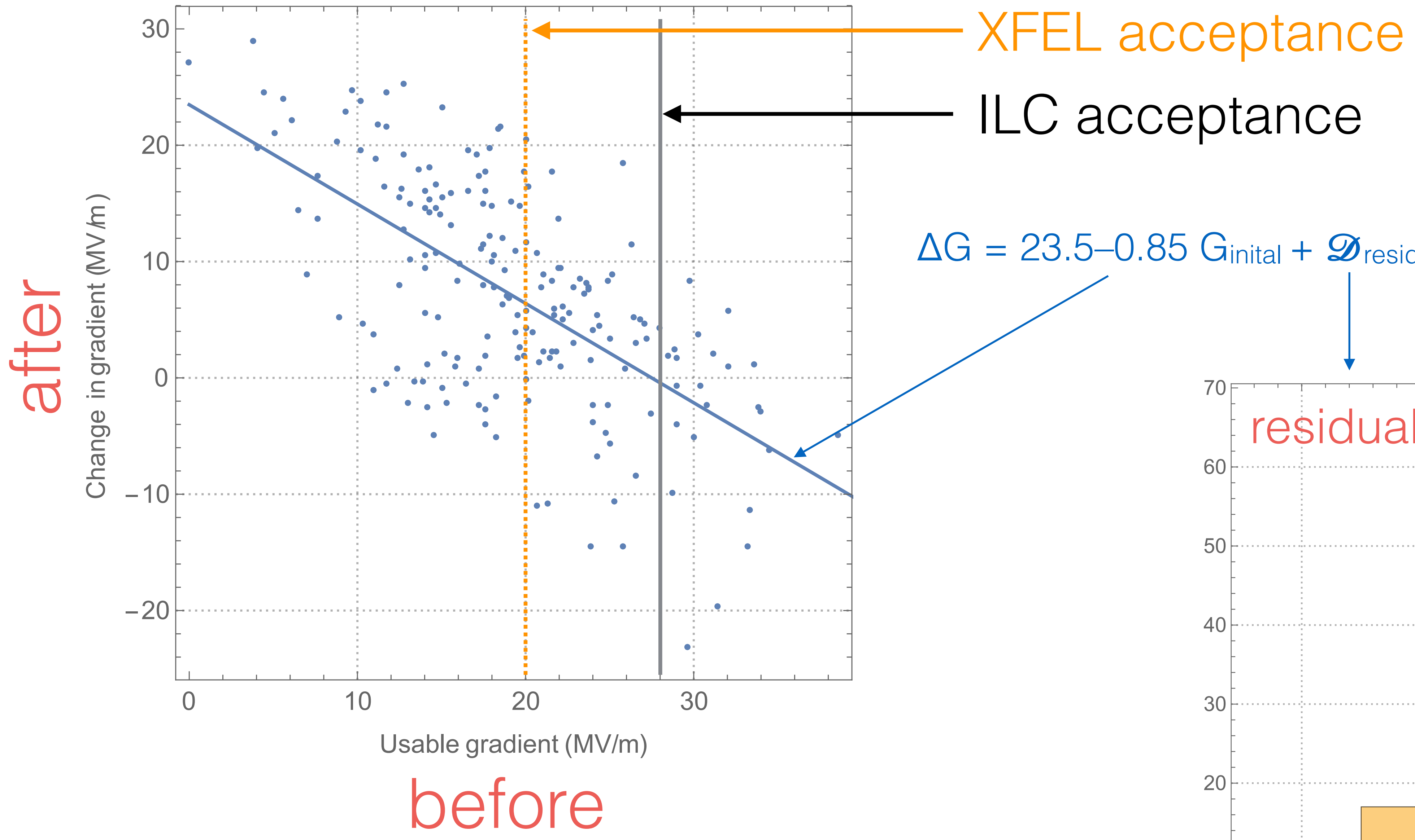
Clearly see difference between RI (final EP) and EZ (flash-BCP)

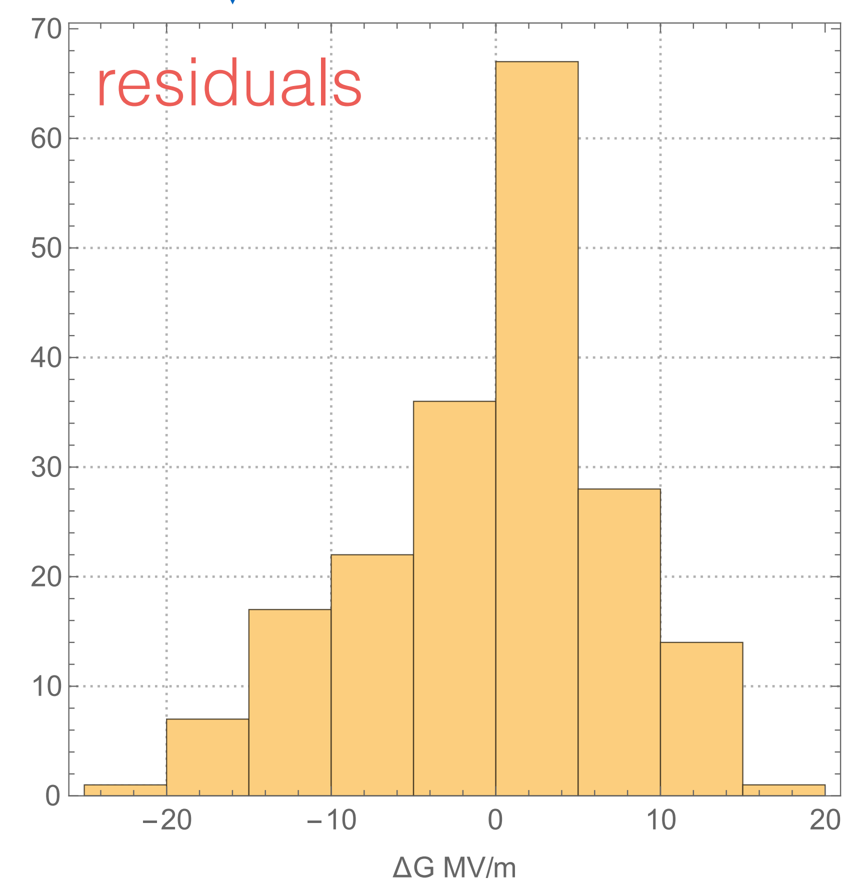
ILC TDR recipe (RI, final EP)

	RI	EZ	Total
Tests	375	368	743
G_{AVG} (MV/m)	33.	29.8	31.4
G_{RMS} (MV/m)	6.6	6.6	6.8
yield @ 20MV/m	94%	89%	92%
yield @ 26MV/m	90%	80%	85%
yield @ 28MV/m	86%	73%	79%



Retreatment model (monte carlo)





Modelled retreatment of cavities
with ≤28 MV/m

Extrapolation to ILC - VT

RI results only (ILC recipe)

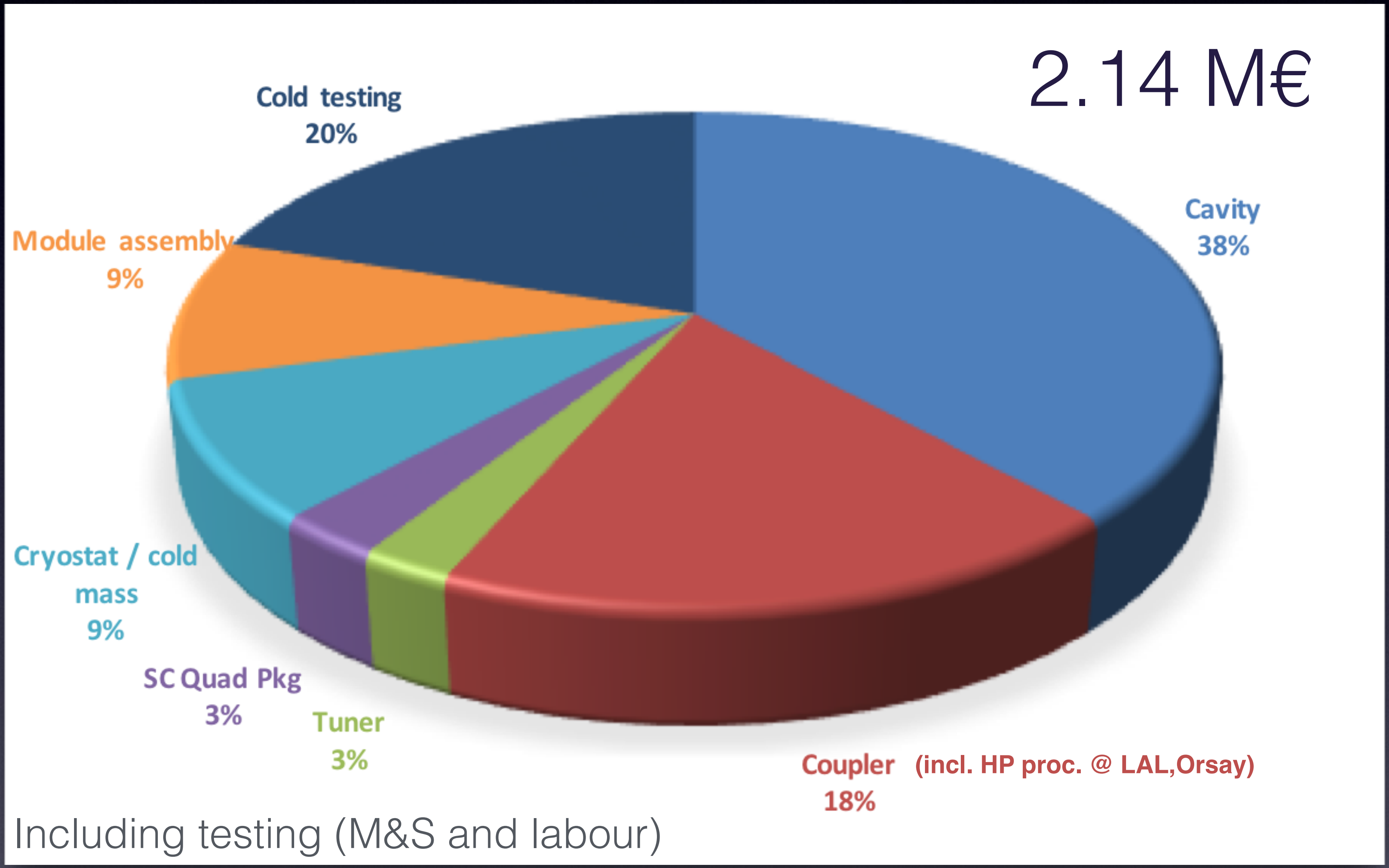
		ILC TDR (assumed)	XFEL max	XFEL usable
First-pass	Yield >28 MV/m	75%	85%	63%
	Average >28 MV/m	35 MV/m	35.2 MV/m	33.5 MV/m
First+Second pass	Yield >28 MV/m	90%	94%	82%
	Average >28 MV/m	35 MV/m	35.0 MV/m ✔	33.4 MV/m ✘
First+Second+third pass	Yield >28 MV/m	-		91%
	Average >28 MV/m	-		33.4 MV/m

but close!

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

→ +$

XFEL cryomodule cost



ILC TDR ~1.3 M€ (2012)

Module cost: XFEL to ILC

XFEL cost

2.13 M€

100 modules in 2 years
1 module / week
100% testing

Extrapolated ILC
European IKC based on 640 module production in 7 years

1.55 M€
(20% uncertainty)

640 modules in 7 years
2 module / week
100% testing

- reuse of existing infrastructure
- reduced infrastructure cost per module
- assumed 95% slope learning curve (8-12%)
- two vendor model

part of study for
"European Action Plan"
(work in progress)

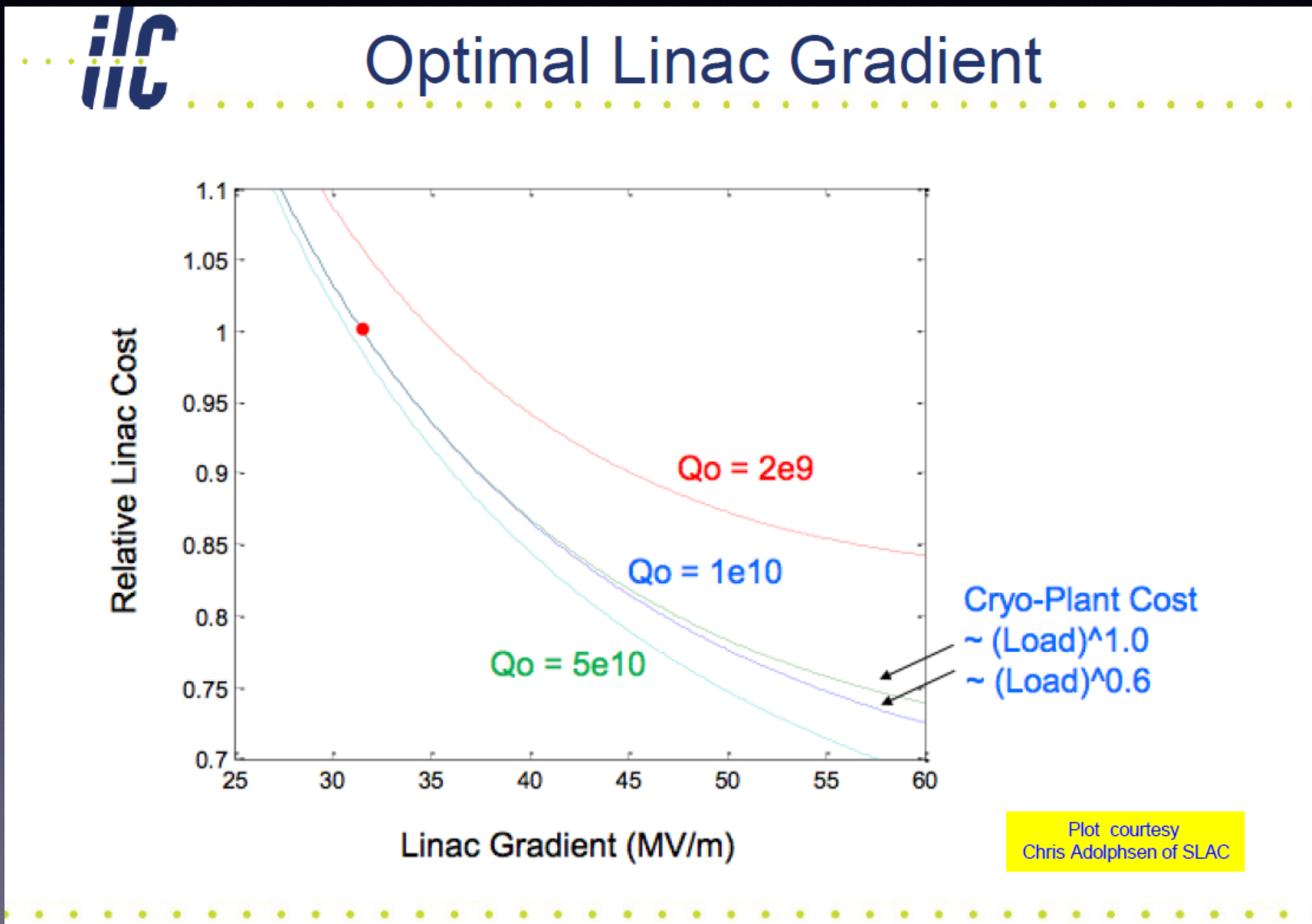
ILC TDR

1.3 M€
(28% uncertainty)

1860 modules in 3 years
12 module / week
33% testing

- reduced infrastructure cost per module
- assumed 95% slope learning curve (8-12%)
- two vendor model
- purpose-built infrastructure for high production rates

SRF cost reduction R&D

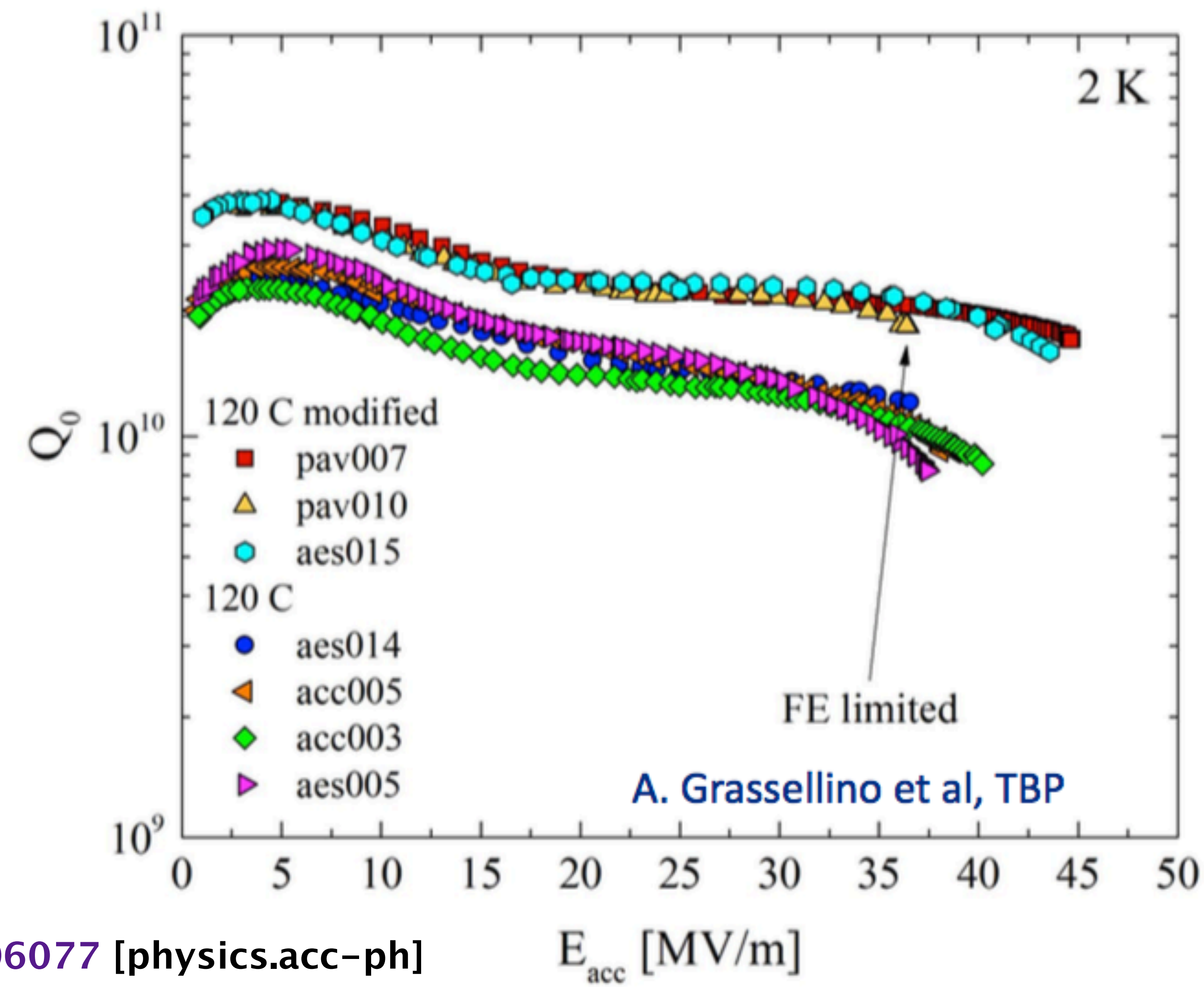


Can we expect higher performance?

(At a reduced cost?)

Nitrogen infusion

120C "modified" bake with N2 – repeatedly highest Q ever measured >2e10 at very high gradients>40 MV/m!



arXiv:1701.06077 [physics.acc-ph]

Nitrogen infusion

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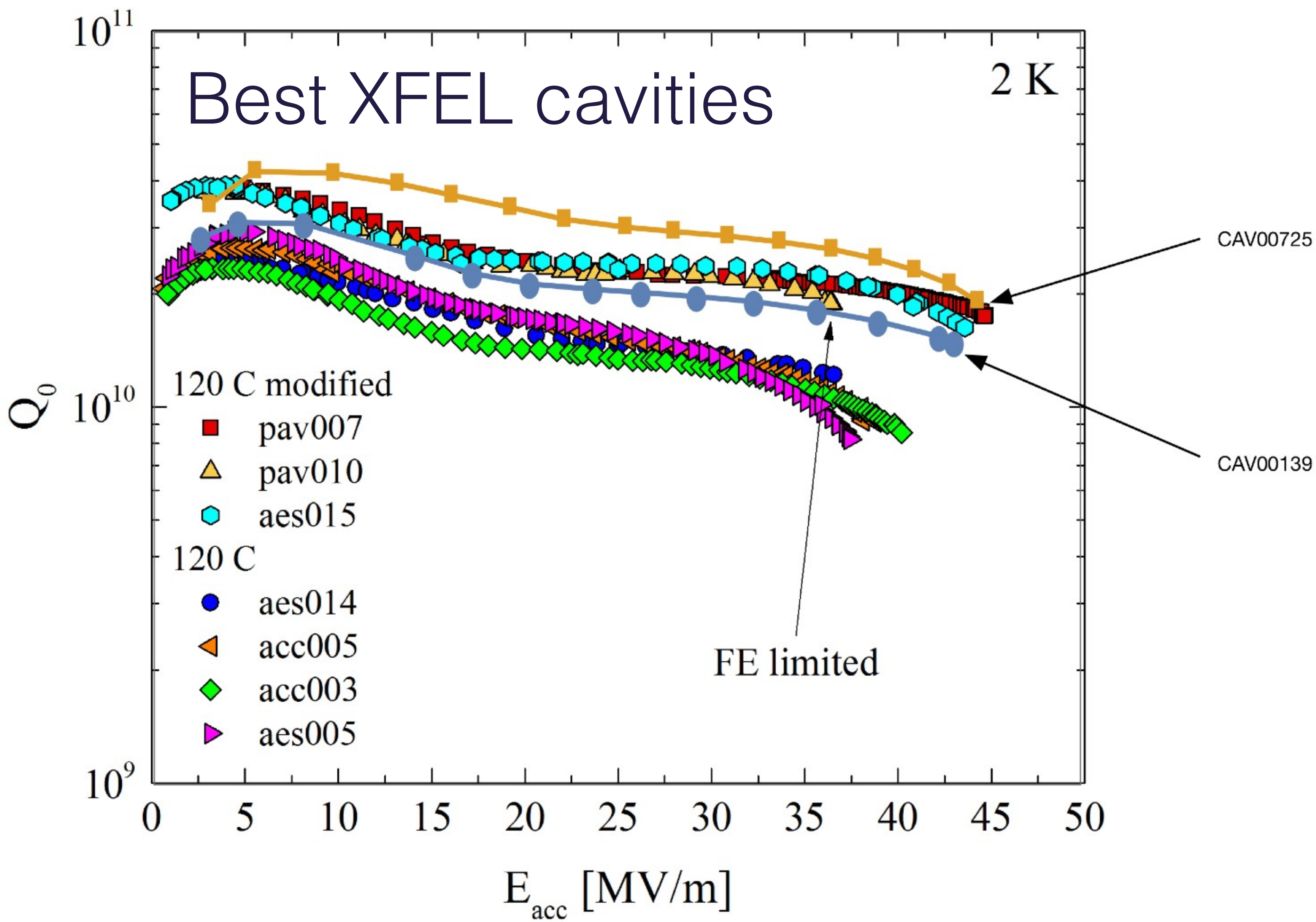
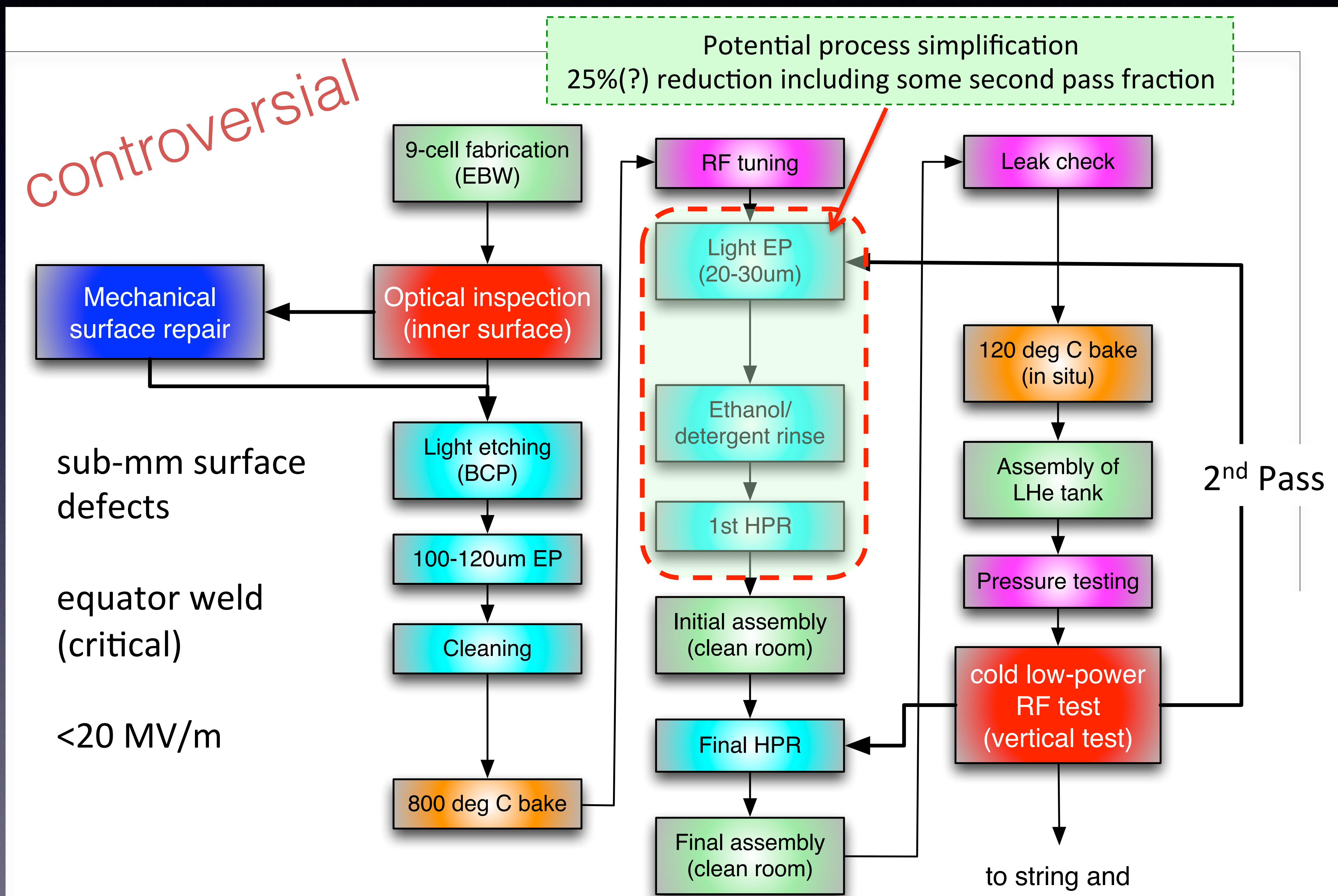
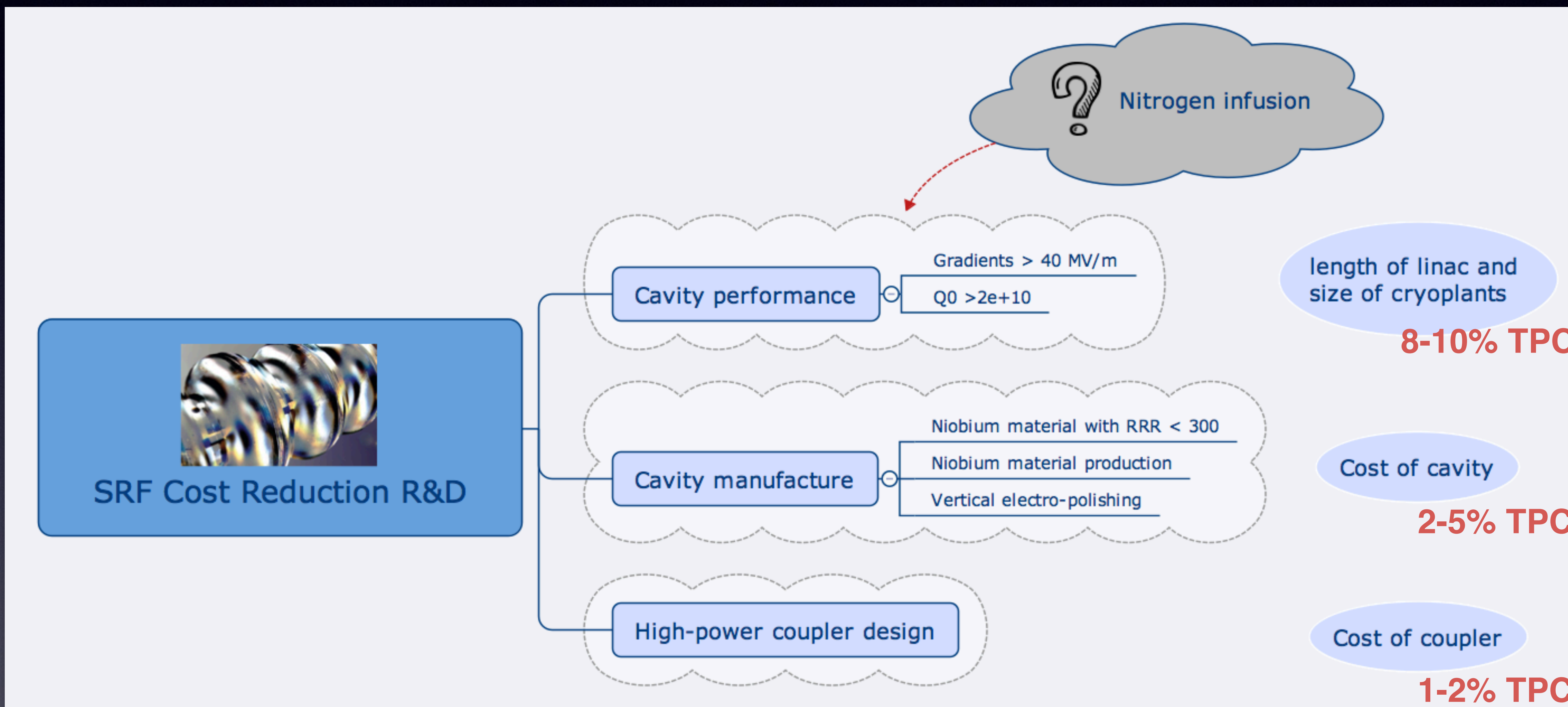


arXiv:1701.(

Not only better —but cheaper!



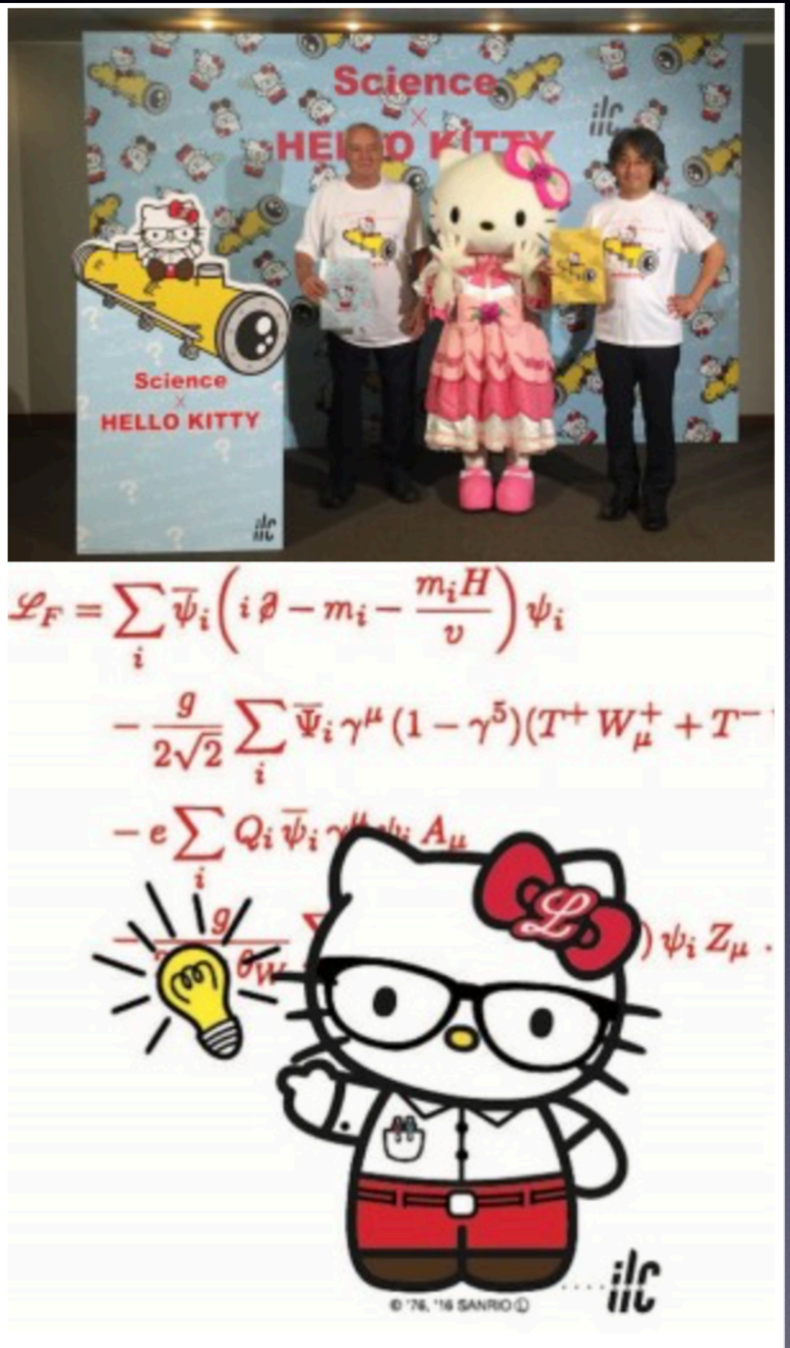
SRF R&D - current focus



XX% TPC ➜ KEK/FNAL guestimate
R&D programme (until 2019)
Under resourced (NW opinion)

ILC Future (Japan)

- MEXT + JSC deliberations & critical review
  - Ongoing since 2014
  - Current focus: Human Resources
  - End in sight?
- "Green light" decision expected ~2018 (or not)
- SCRF R&D plan ('cost reduction) now until ~2020
  - but very little resource worldwide
- Discussions and re-evaluation of energy staging
  - 250 GeV first stage
  - Looking for ~40% cost reduction over TDR price!

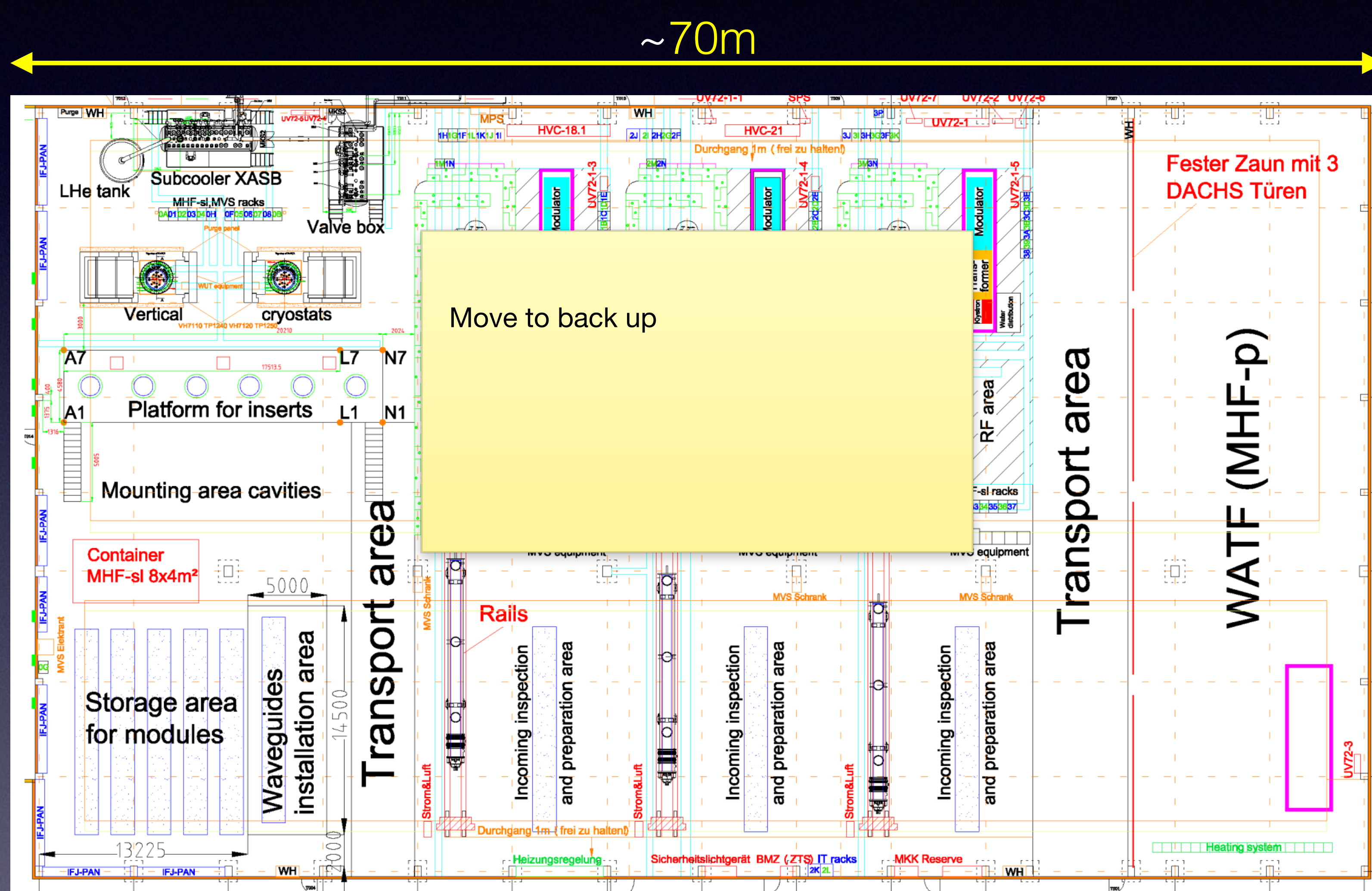


Final Comments

- It's been a long road…
- TESLA technology is now mature and industrialised
    - almost 'off the shelf' (cf LCLS-II)
- Performance is very close to ILC requirements
    - But not the cost!
    - Larger scale industrialisation will help if planned correctly
- New SRF 'breakthroughs' may bring significant cost benefits
    - higher gradients, higher quality factors
    - but it's industrial yield that matters
- Clearly strong interest in Japan in hosting ILC as an international project
    - But reducing the (TDR) cost is a clear priority
    - Staged energy approach being active promoted
    - Situation should clarify itself by end of 2018

Thank you for your attention 😀

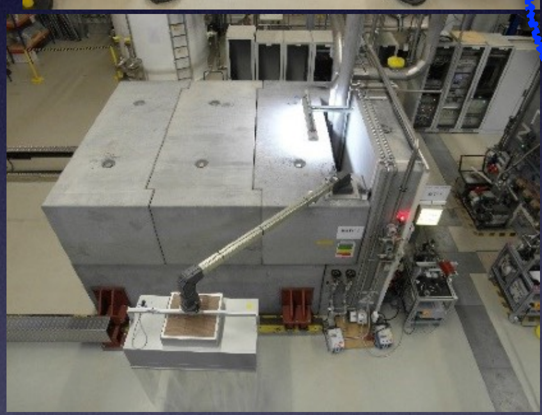
Accelerator Module Test Facility (AMTF) at DESY

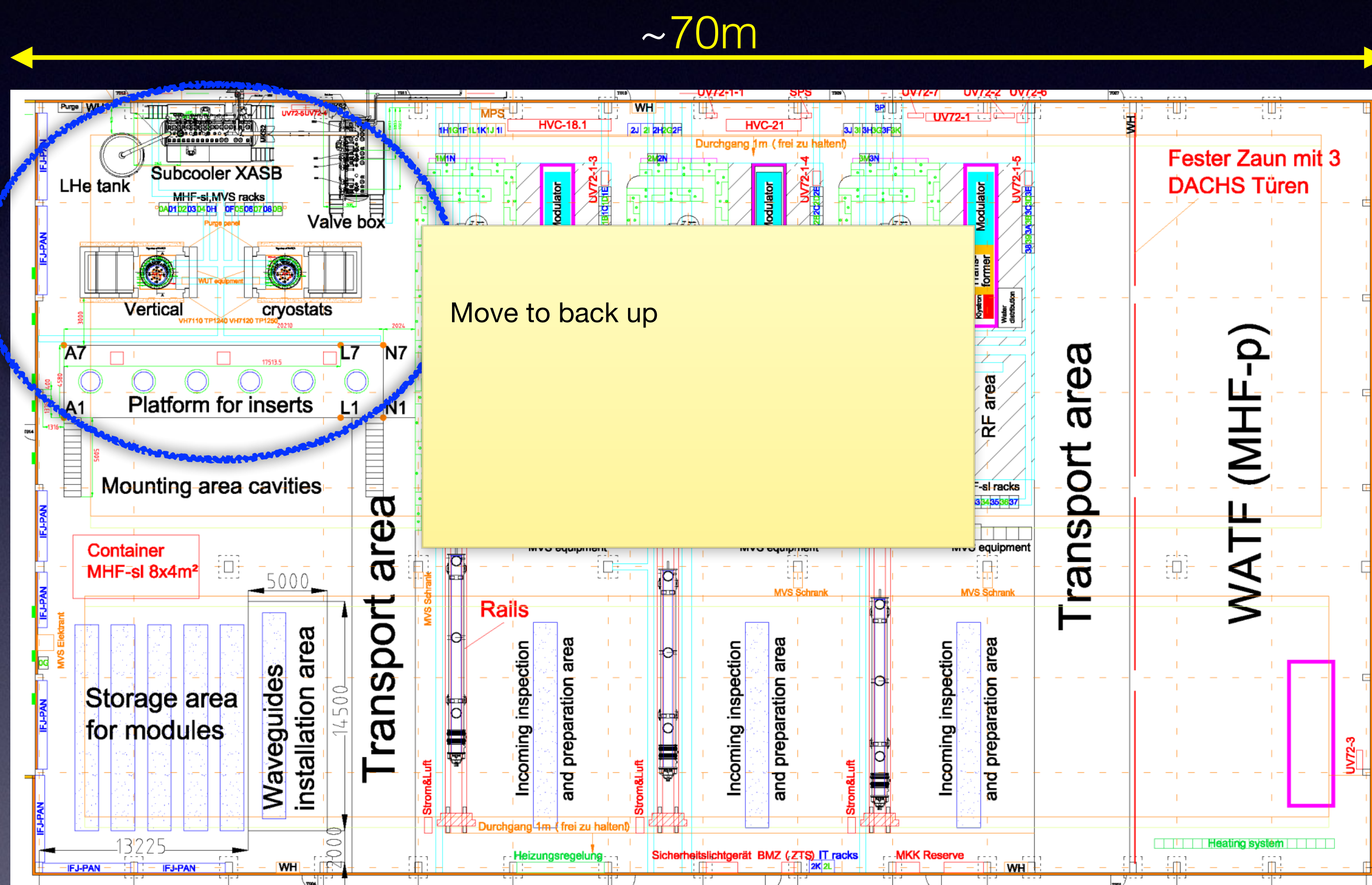


Purpose built infrastructure: 8 cavity acceptance tests / week

1 cryomodule test / week

Accelerator Module Test Facility (AMTF) at DESY





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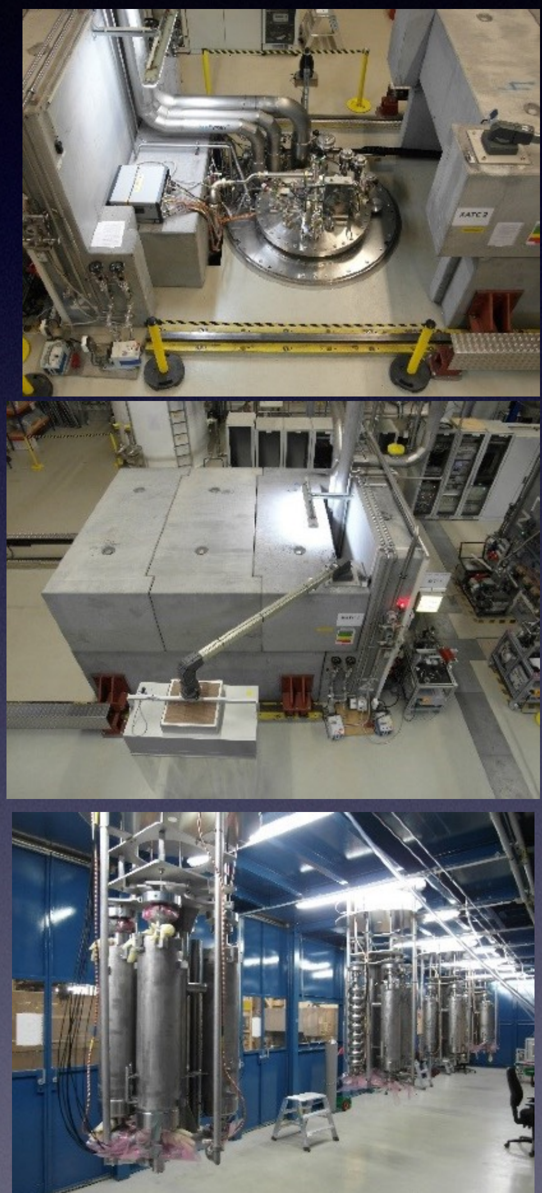

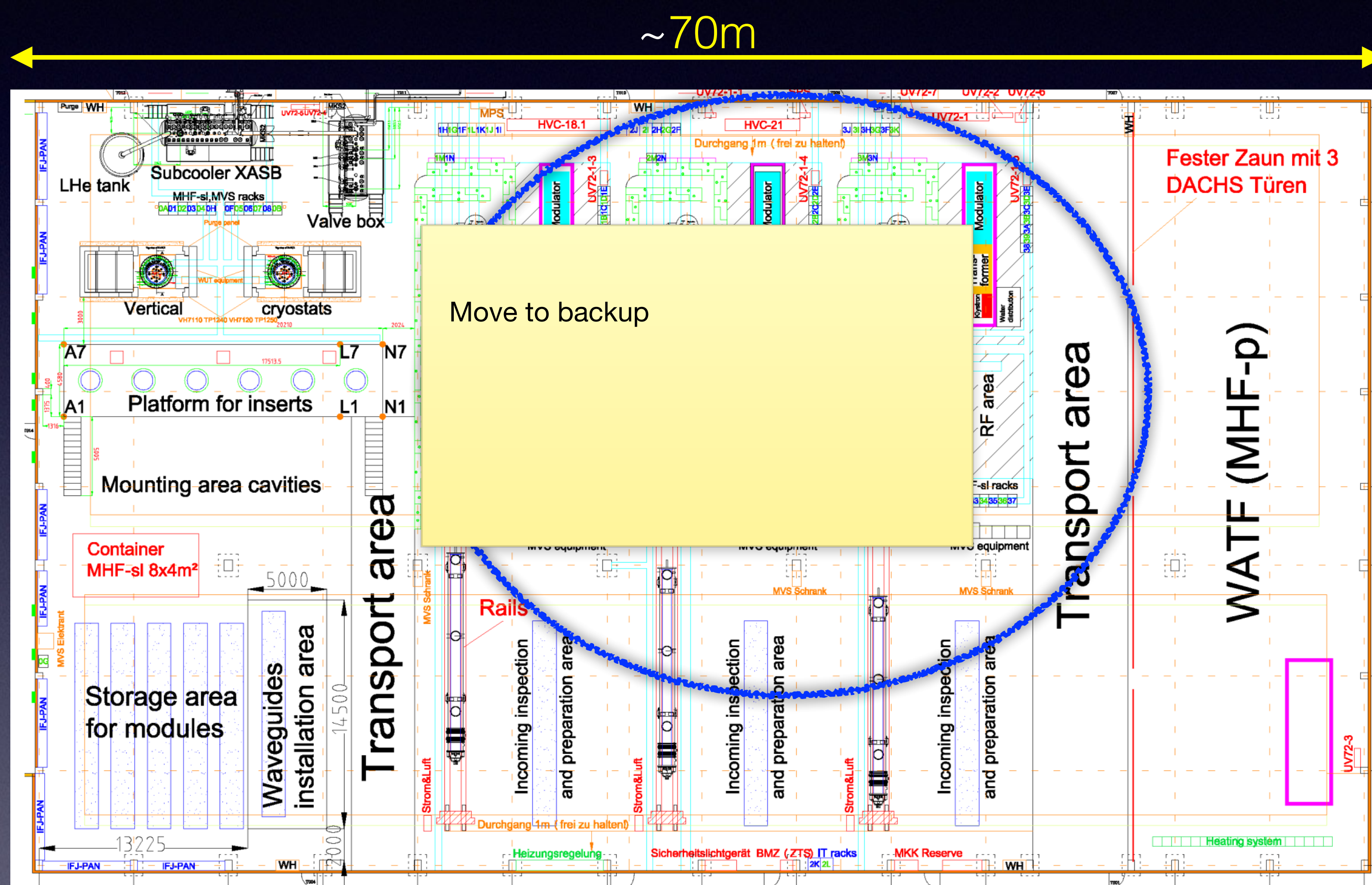

Purpose built infrastructure: 8 cavity acceptance tests / week

1 cryomodule test / week

Historical performance comparison