EFFECT OF THE COOLDOWN VELOCITY ON THE PERFORMANCE OF SUPERCONDUCTING CAVITIES

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DER FORSCHUNG | DER LEHRE | DER BILDUNG

DESY.

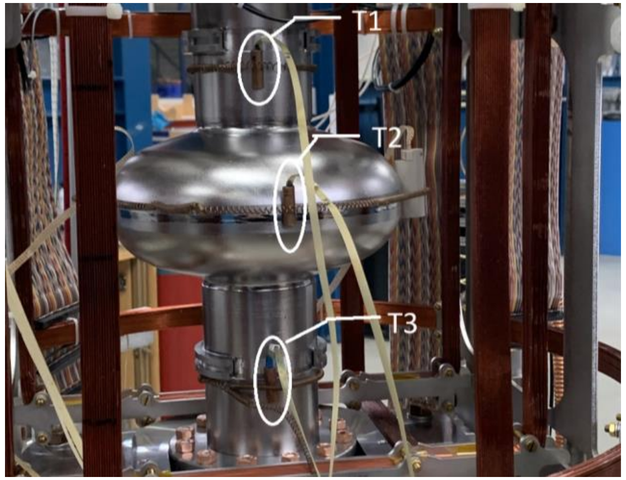
AGENDA

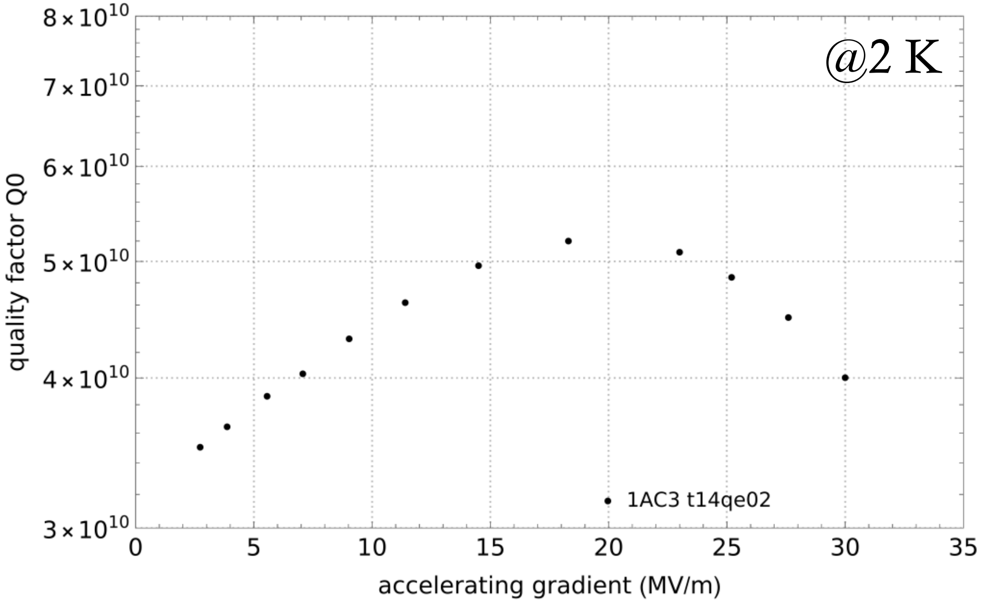
01	02	03	04	05
Introduction Cavities Measurements	Motivation Upgrade EuXFEL	Analysis Tool	Results Performance	Conclusion

INTRODUCTION

CAVITIES

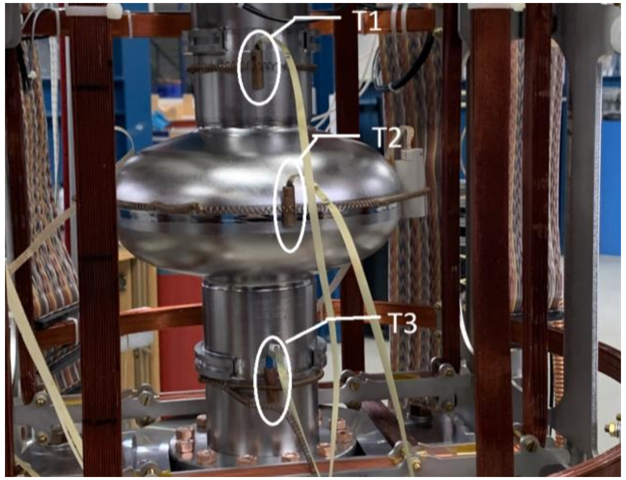
- TESLA shaped
- Resonant frequency 1.3 GHz
- Figures of merit:
  Quality factor Q_0
  Accelerating gradient E_{acc}
  Residual resistance R_{res}
- $R_{surface} = R_{BCS} + R_{flux} + R_{res}$
- Mid-T heat treated, ~3h @300-350 °C
- 4 cavities investigated

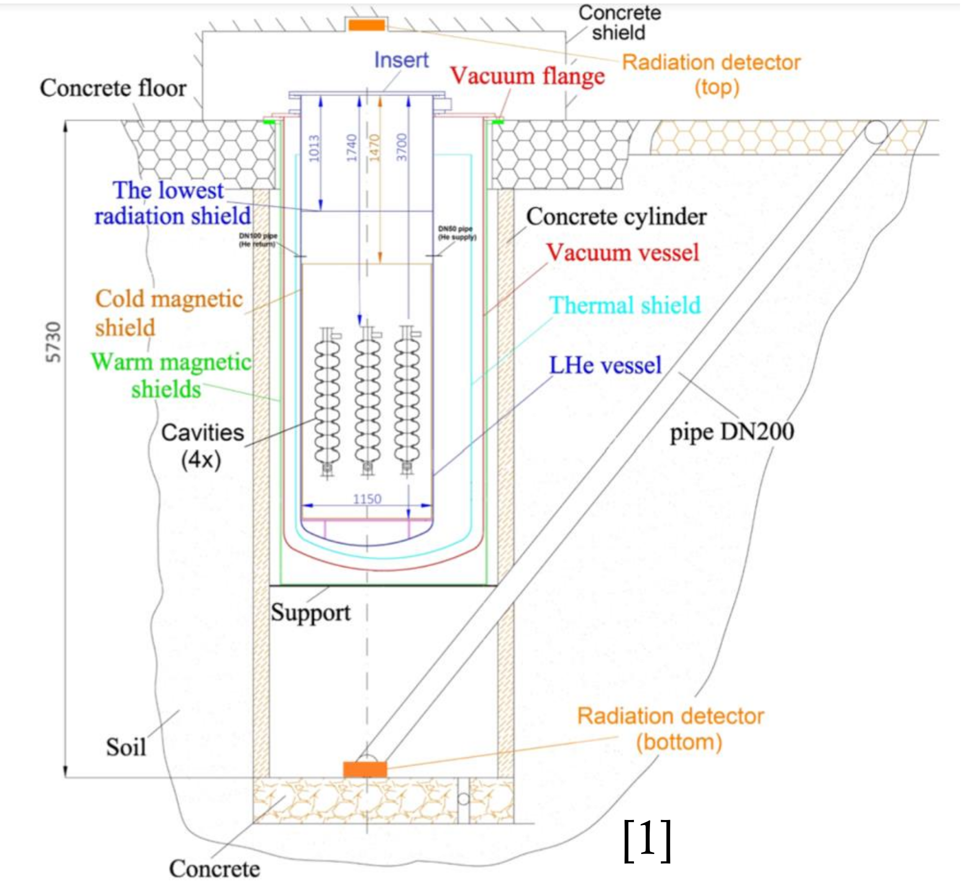




COOLDOWN IN THE VERTICAL CRYOSTAT

- Cavities are positioned vertically
- Temperature sensors on the cavity shielded with a copper tube
- Only single cavity
- Large helium volume
- Filled from the bottom



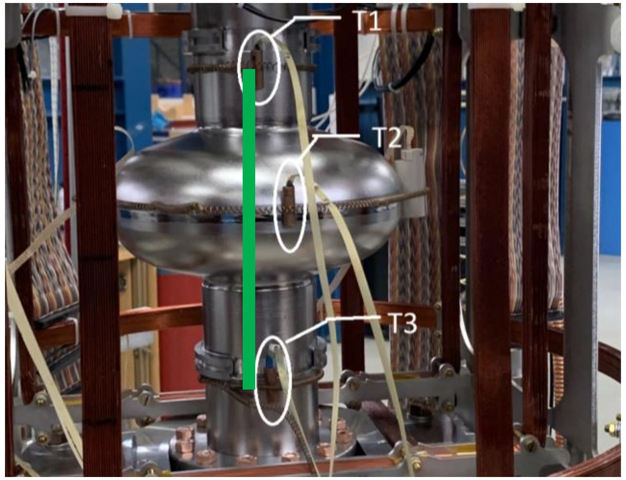


[1]

COOLDOWN VARIABLES

- Measured temperature using Cernox 1030 HT sensors
- Cooldown velocity
  - temperature versus time
  - interval is from 10.7 K to 7.7 K ($T_c \pm 1.5$ K)
- Spatial Temperature Gradient
  - temperature difference at T_c
  - divided by distance ~225 mm (T sensor 1 - T sensor 3)

~225mm



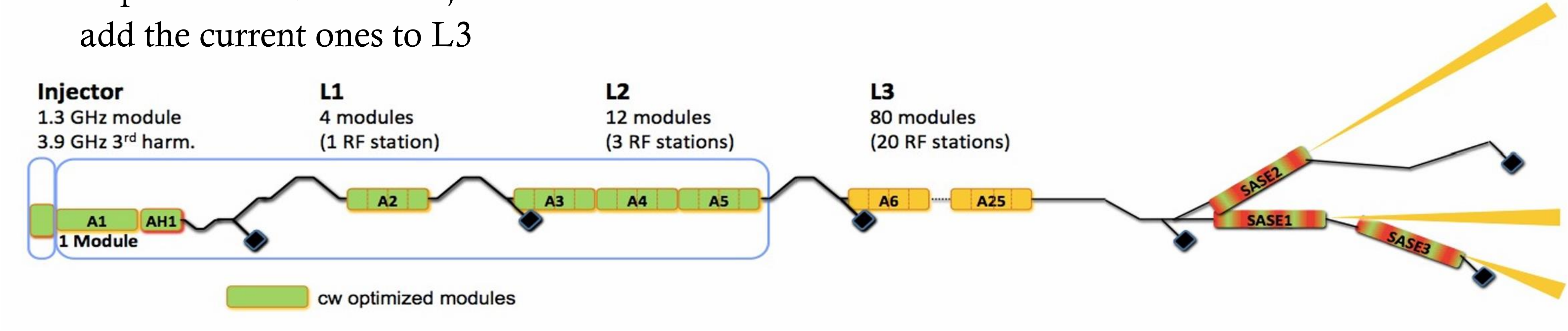
MEASUREMENT PRINCIPLES

- Quality factor (Q_0) is calculated from power
  used to evaluate constant for E_{acc} calculation (at $\leq 5\ \frac{\mathrm{MV}}{\mathrm{m}}$)
- Accelerating gradient is calculated from constant and power
- Residual resistance is evaluated by a fit over
  the quality factor (at $\sim 4\ \frac{\mathrm{MV}}{\mathrm{m}}$) between 2 K to 1.4 K

MOTIVATION

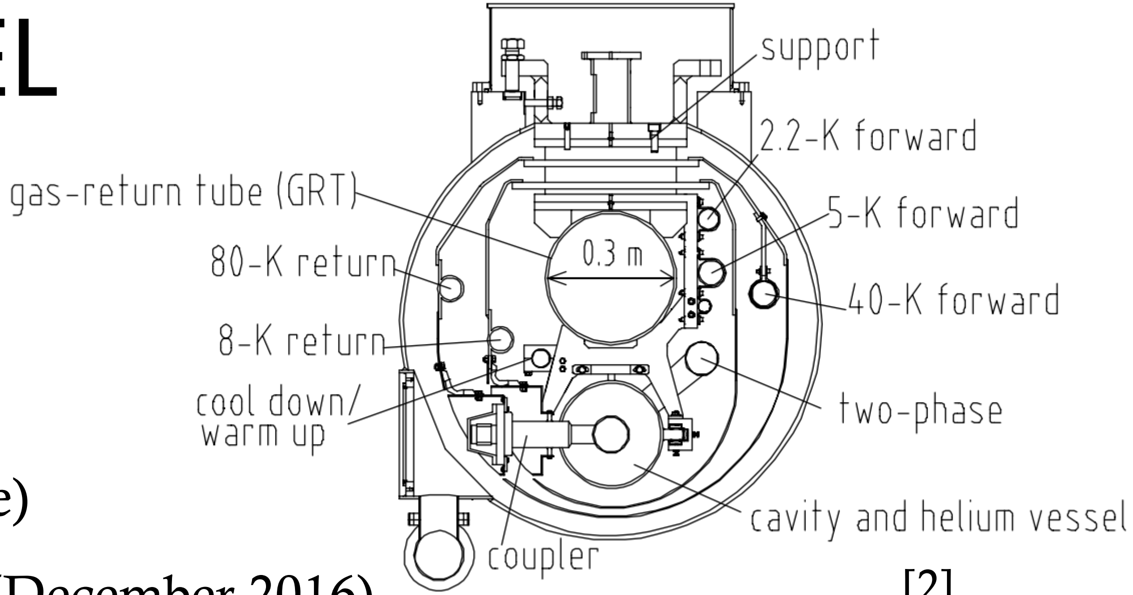
EUROPEAN XFEL UPGRADE

- Add new the operation modes High Duty Cycle (HDC) and/or Continues Wave (CW)
- Requirements:
  Higher quality factor $Q_0 > 3 \cdot 10^{10}$
  Accelerating gradient $E_{acc} > 20\,\frac{\mathrm{MV}}{\mathrm{m}}$
- Replace first 17 modules;
  add the current ones to L3

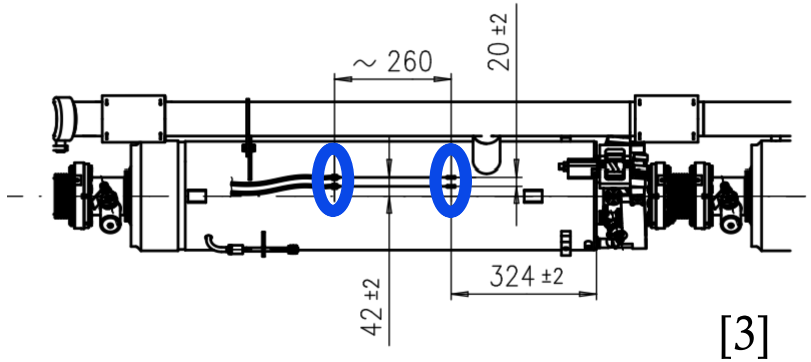


COOLDOWN OF THE EUXFEL

- Cavities are positioned horizontally
- Temperature sensors on the Cryomodule tank
- Cavities are in row (8 nine-cell cavities per module)
- Cooldown of modules was performed in parallel (December 2016)

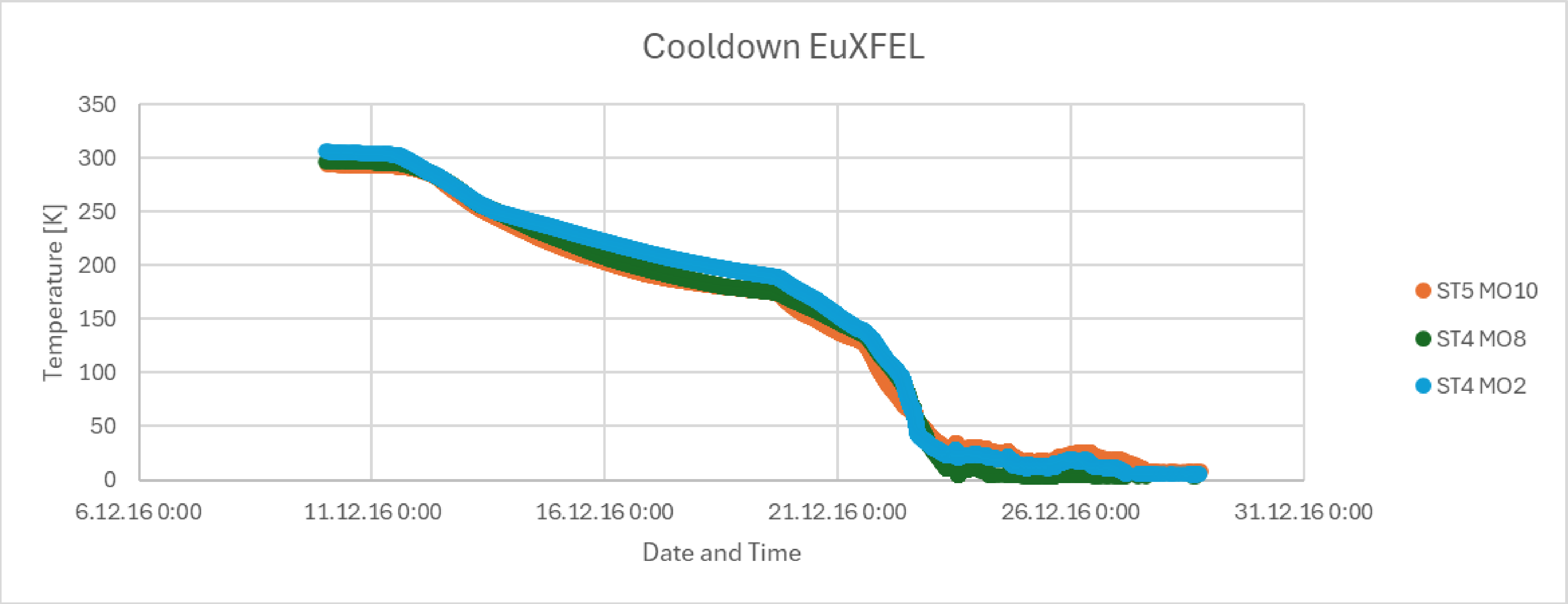


[2]

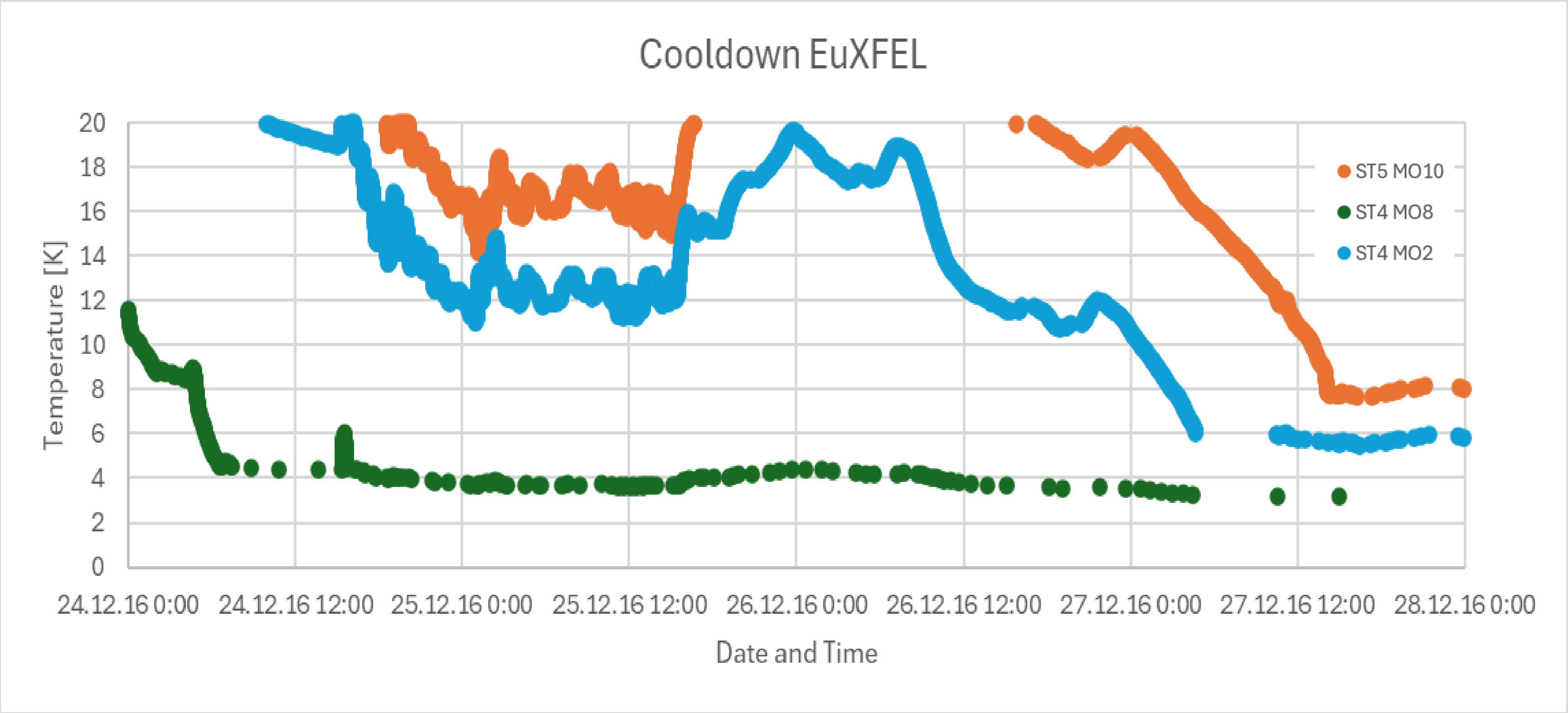


[3]

COOLDOWN OF THE EUXFEL



COOLDOWN OF THE EUXFEL



- T below 9.2 K varies in date
- Cooldown velocity between 0.1 $\frac{\text{mK}}{\text{s}}$ and 0.5 $\frac{\text{mK}}{\text{s}}$

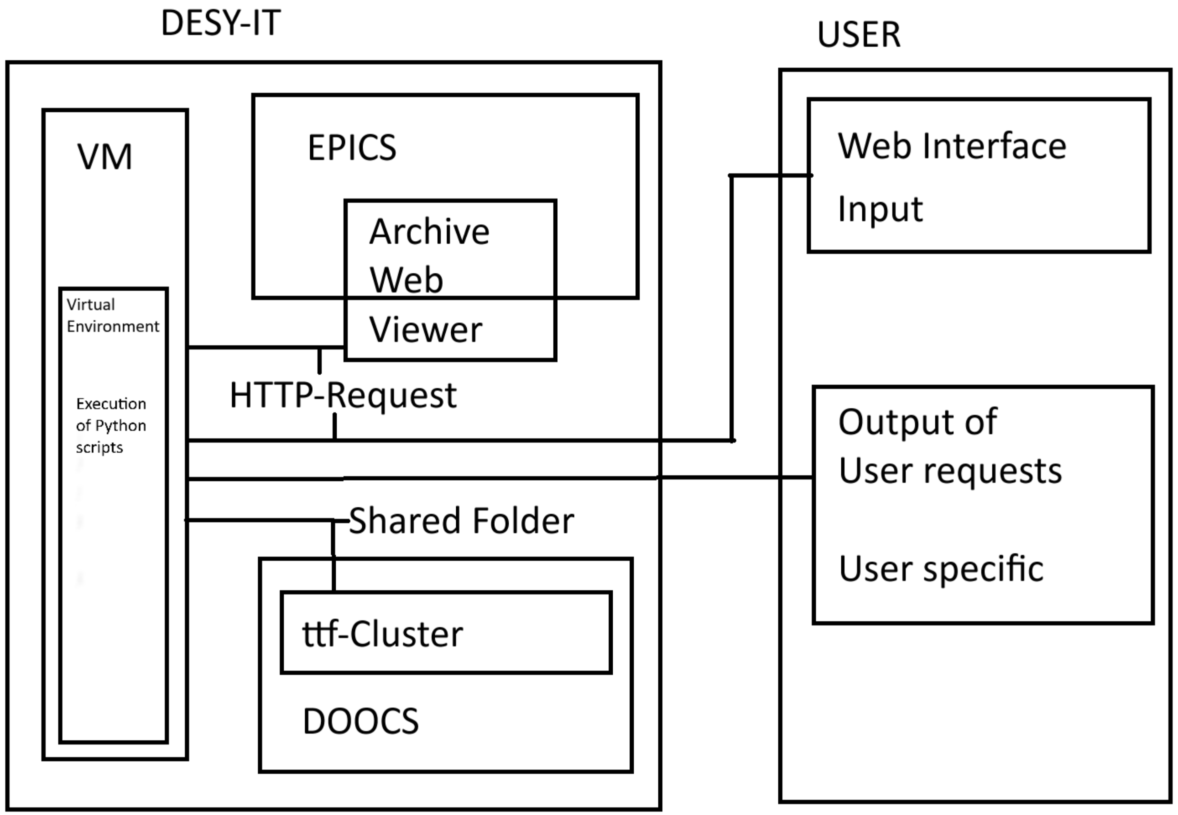
[3]

ANALYSIS TOOL

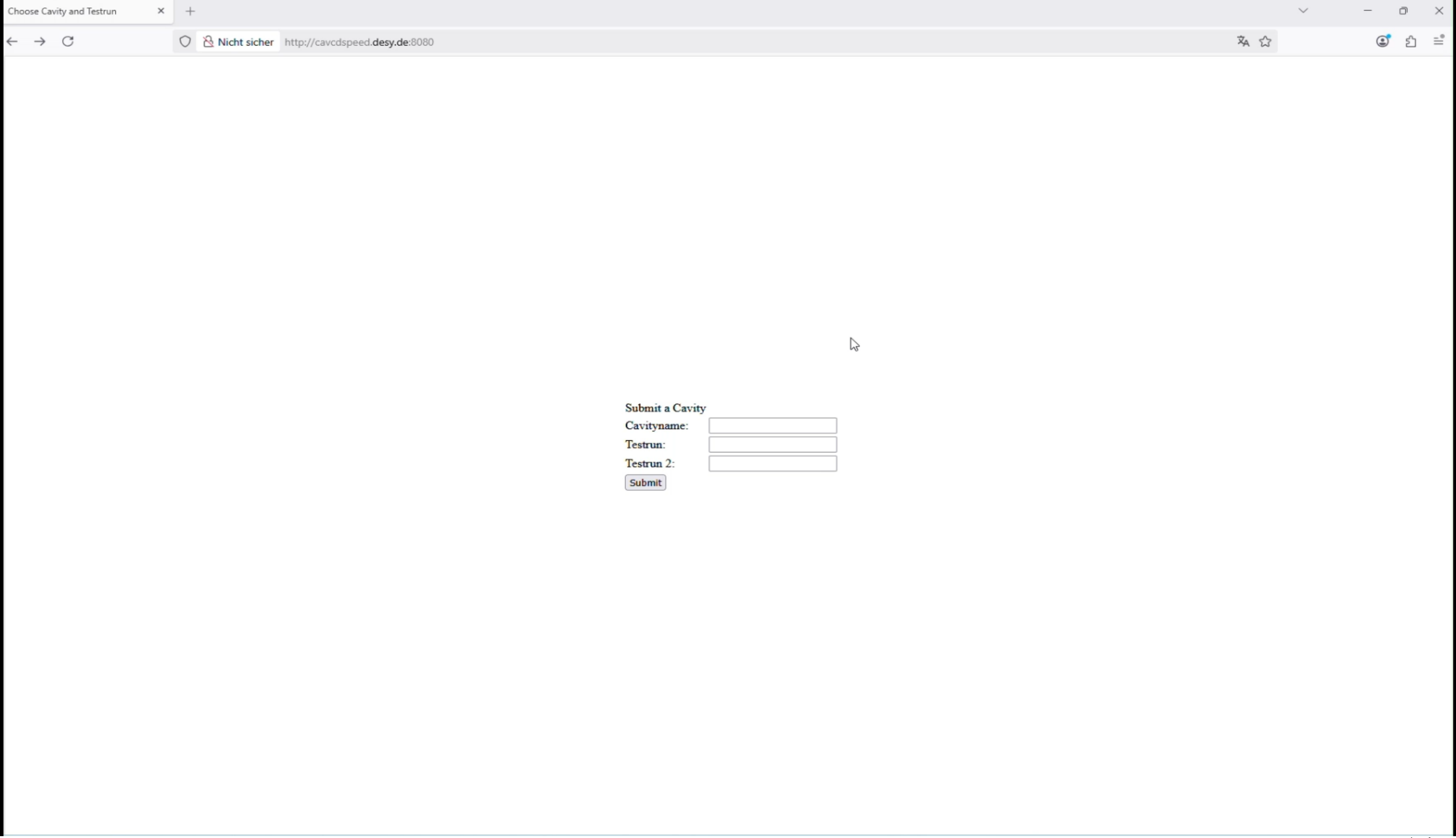
GOALS

- Gather temperature and measurement data
- Represent cooldown in few variables
- Automate cooldown variable calculation
- Should work for past and future measurements

INTERFACING



- Program uses data from two file-systems
- Runs on a virtual machine
- Requests handled sequentially
- Output of collection script is saved

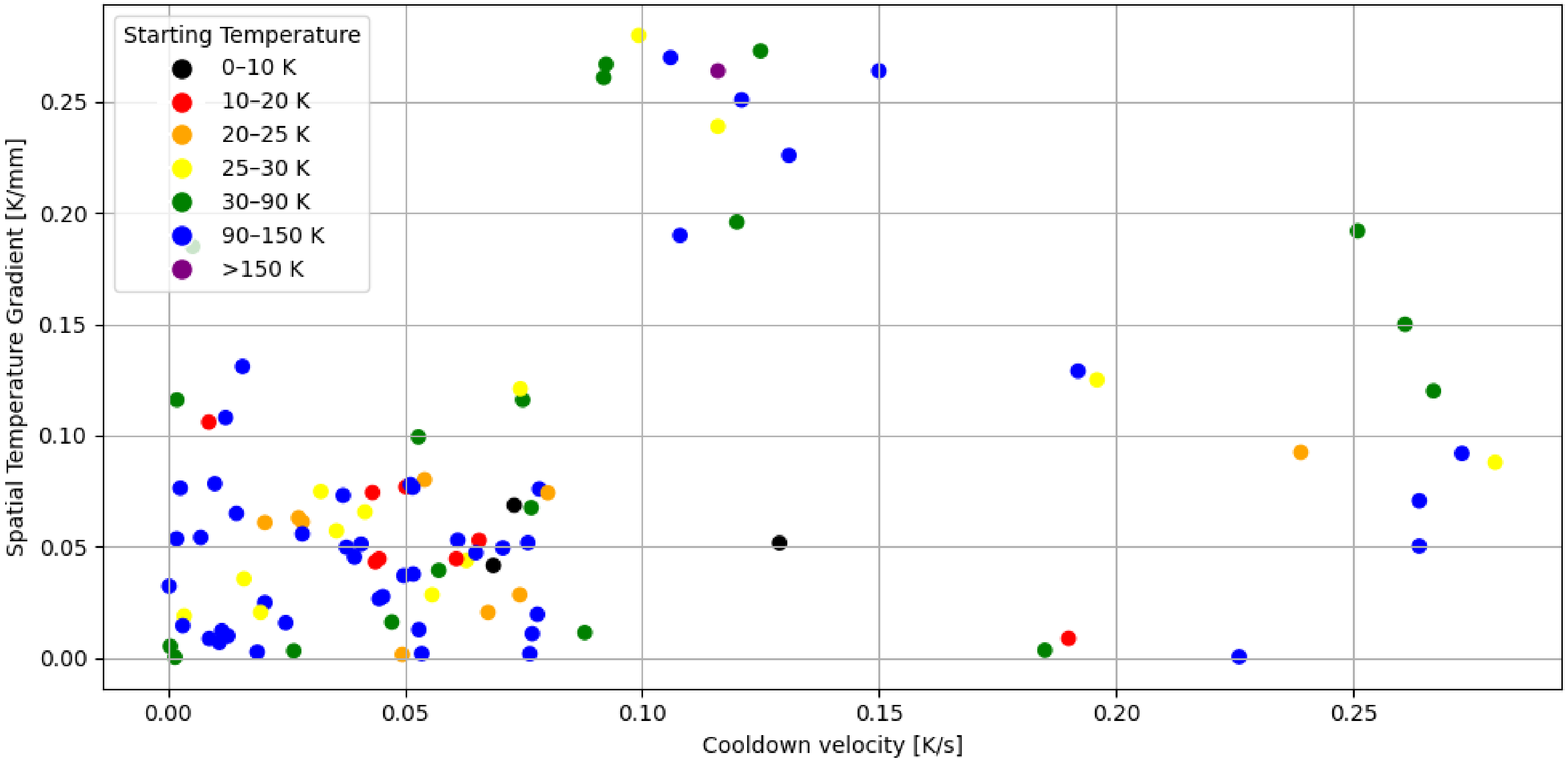

Choose Cavity and Testrun
Nicht sicher
http://cavcdspeed.desy.de:8080
Submit a Cavity
Cavityname:
Testrun:
Testrun 2:
Submit

RESULTS

UNCERTAINTY

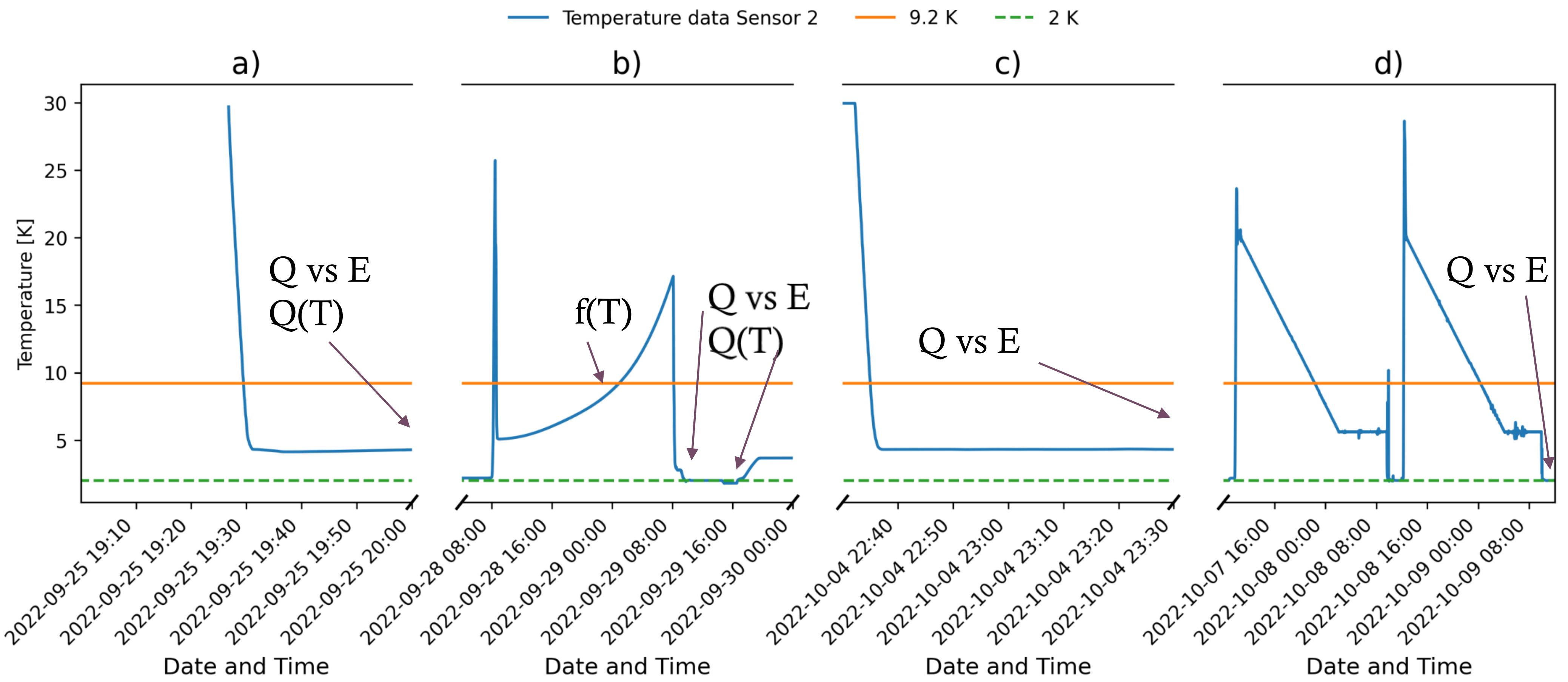
- Uncertainty for Q_0 is 6%, E_{acc} is 3% (same calibration and vertical test) [1]
  20% Q_0 and 10% E_{acc} (change of calibration and test) [1]
- Uncertainty of cooldown velocity is <0.4%
  statistical error of the temperature measurements $\pm$5 mK [4]
  worst linear approximation (2.5 K range, 2 points)
- Systematic error of at most 0.3 K (not relevant for cooldown velocity) [5]
  lower at cryogenic temperatures < 10 mK
  influences the spatial temperature gradient

COOLDOWN VELOCITY VS. SPATIAL TEMPERATURE GRADIENT

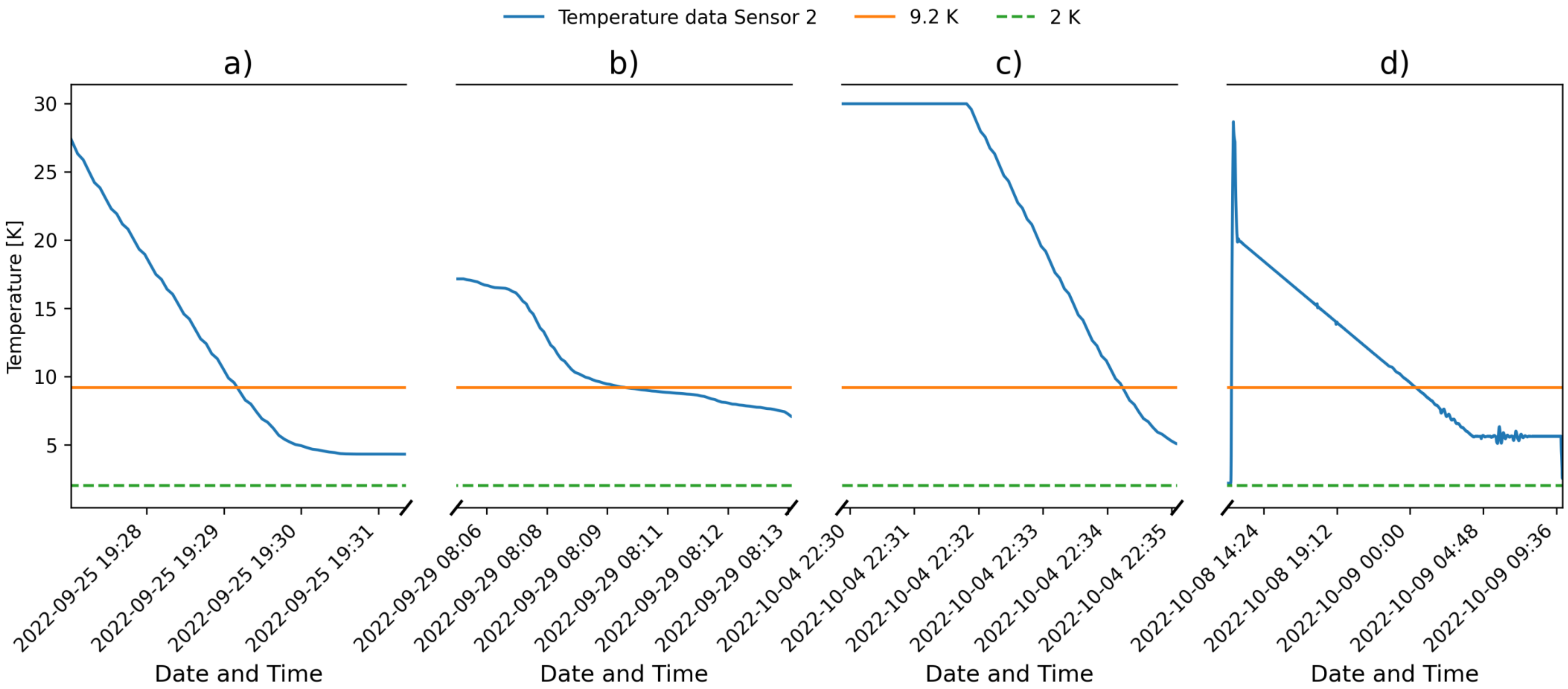


- Pearson correlation coefficient r = 0.3, p = 0.0012
- Between 90-150 K due to waiting period at ~100 K
- At 10-20 K after f(T)
- Thermocycling for all 20-25 K , 25-30 K and 30-90 K ranges

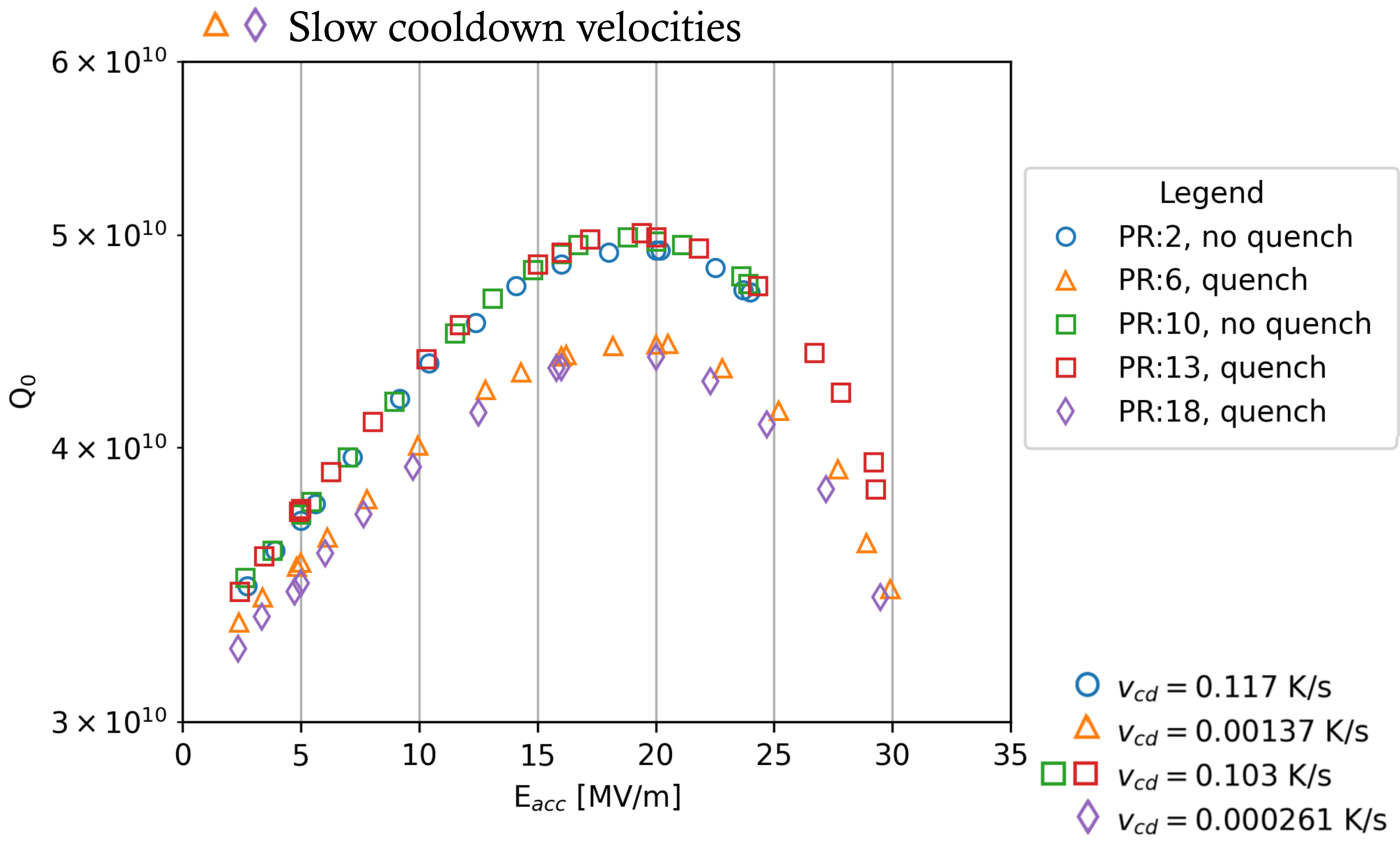
COOLDOWN OF 1AC3



COOLDOWN OF 1AC3



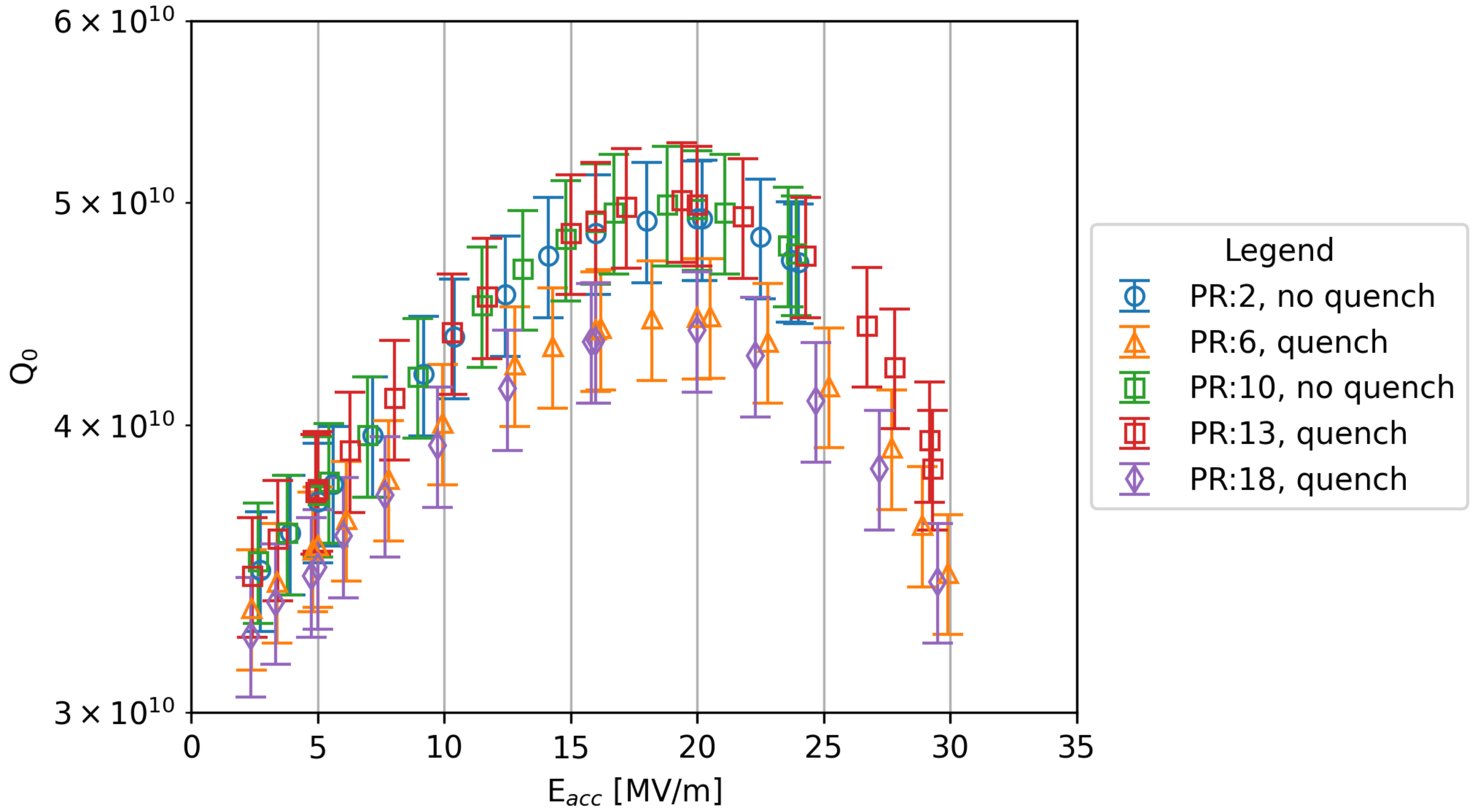
LOSS IN QUALITY FACTOR



- Cavity 1AC3t12
- Loss of quality factor Q_0 related to cooldown velocity
- Reset after a new warm up to over T_c
- No degradation due to quench

LOSS IN QUALITY FACTOR

△ ◊ Slow cooldown velocities



- Cavity 1AC3t12
- Loss of quality factor Q_0 related to cooldown velocity
- Reset after a new warm up to over T_c
- No degradation due to quench

○ $v_{cd} = 0.117$ K/s

△ $v_{cd} = 0.00137$ K/s

□ □ $v_{cd} = 0.103$ K/s

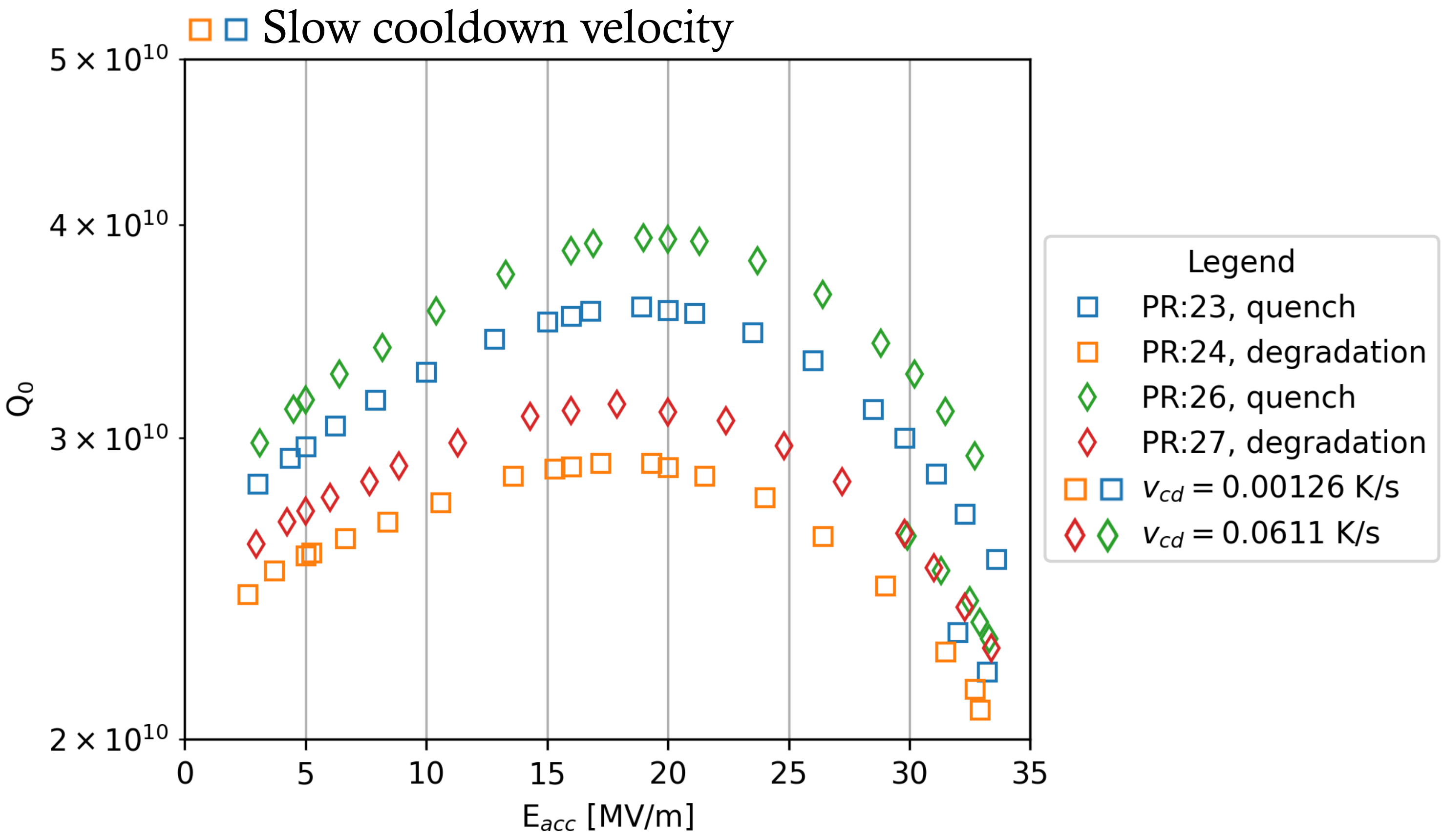
◊ $v_{cd} = 0.000261$ K/s

LOSS IN QUALITY FACTOR

power raise	v_{cd} [K/s]	Q_0 @ 20 MV/m
02	0.106	4.92e+10
10	0.103	4.97e+10
13	0.103	4.99e+10
14	0.103	4.82e+10
5	0.00866	4.58e+10
6	0.00866	4.46e+10
17	0.000261	4.40e+10
18	0.000261	4.40e+10
		$\Delta Q_{0,max,20}$ [%]
$2 \div 13$	0.106	1.4
$10 \div 13$	0.103	0.4
$13 \div 13$	0.103	0.0
$14 \div 13$	0.103	3.4
$5 \div 13$	0.00866	8.2
$6 \div 13$	0.00866	10.6
$17 \div 13$	0.000261	11.8
$18 \div 13$	0.000261	11.8

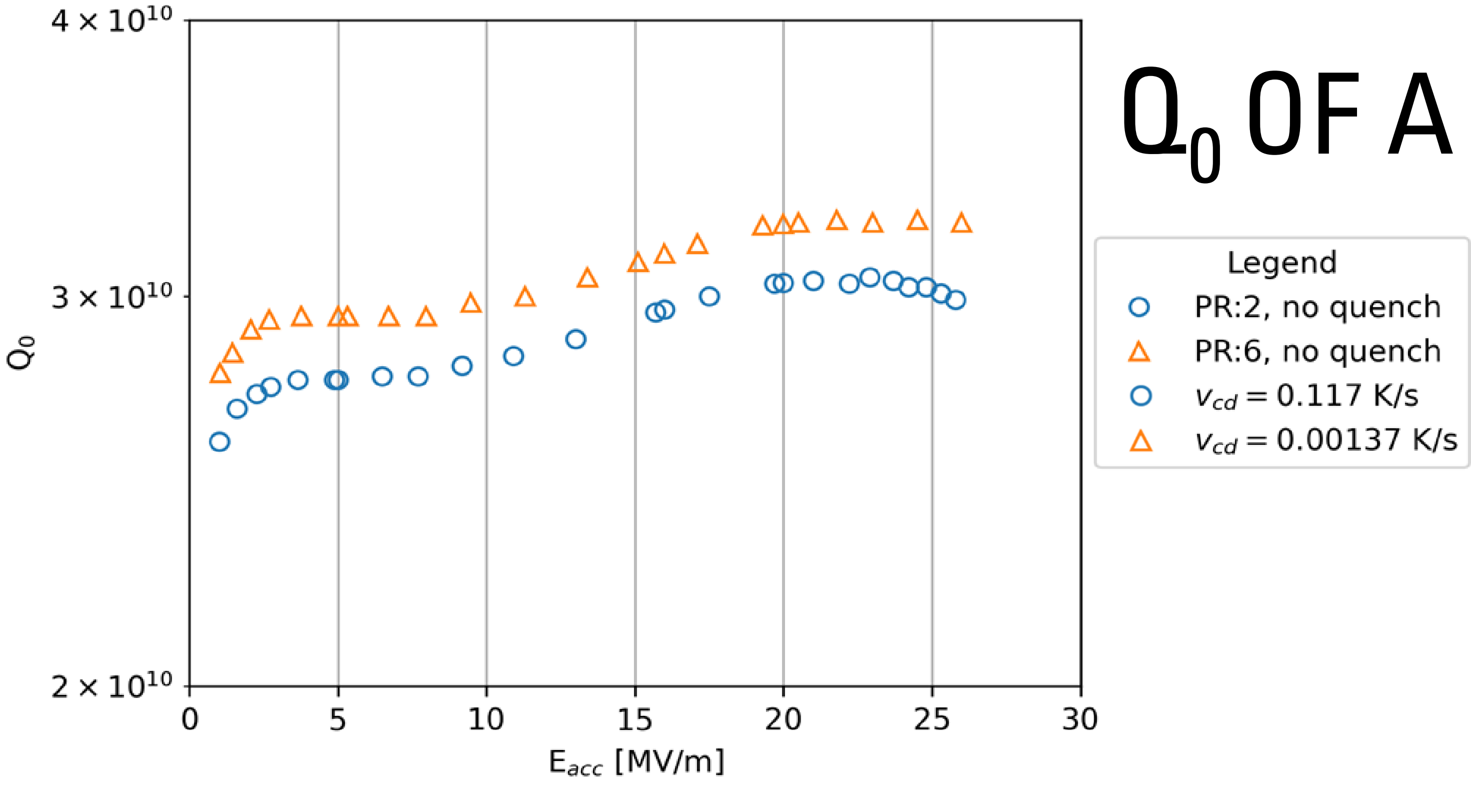
- Compared to maximum quality factor achieved
- Loss of ~12% with slowest cooldown
- Loss changes with cooldown velocity
- Velocity in range of the EuXFEL cooldown

DEGRADATION OF Q_0



- Cavity 1RI06t06
- Degradation of the quality factor Q_0 due to quenching
- Loss of quality factor is additive
- Accelerating gradient at quench is not dependent on the cooldown velocity

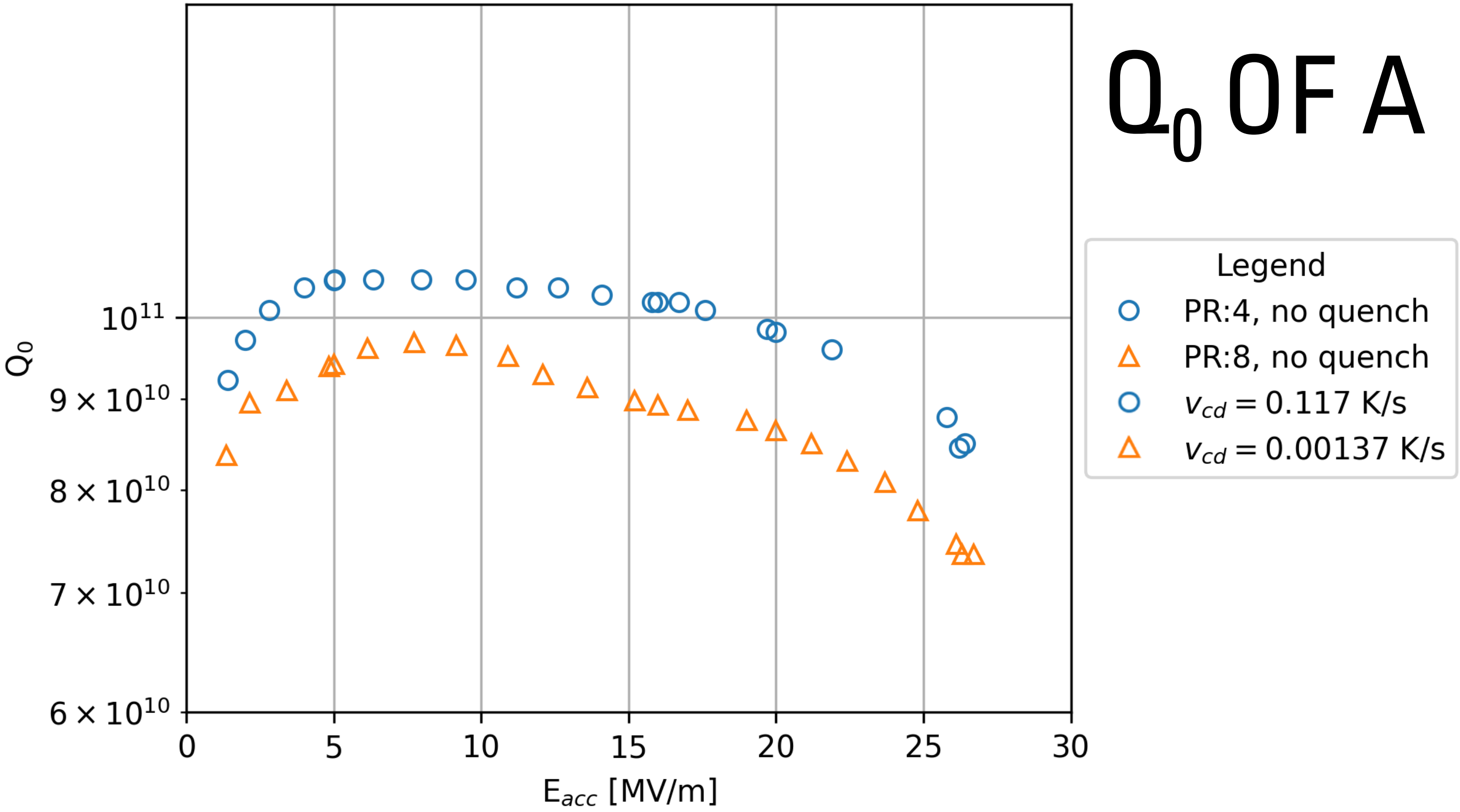
Q_0 OF A NINE CELL CAVITY



- CAV00029 EuXFEL cavity retreated
- Increase in quality factor >6%

power raise	v_{cd} [K/s]	Q_0@5MV/m	Q_0@16MV/m	Q_0@20MV/m
2	0.117	2.75e+10	2.96e+10	3.04e+10
6	0.00137	2.94e+10	3.14e+10	3.24e+10
		$\Delta Q_{0,max,5}$ [%]	$\Delta Q_{0,max,16}$ [%]	$\Delta Q_{0,max,20}$ [%]
$2 \div 2$	0.117	0.0	0.0	0.0
$6 \div 2$	0.00137	gain of 6.9	gain of 6.1	gain of 6.6

Q_0 OF A NINE CELL CAVITY



- Measured at 1.5 K
- Loss in quality factor
- Increase in R_{res}
- Getting remeasured

power raise	v_{cd} [K/s]	Q_0@5MV/m	Q_0@16MV/m	Q_0@20MV/m
4	0.117	1.05e+11	1.02e+11	9.82e+10
8	0.00137	9.42e+10	8.93e+10	8.64e+10
		$\Delta Q_{0,max,5}$ [%]	$\Delta Q_{0,max,16}$ [%]	$\Delta Q_{0,max,20}$ [%]
$4 \div 4$	0.117	0.0	0.0	0.0
$8 \div 4$	0.00137	10.3	12.5	12.1

RESIDUAL RESISTANCE

- R_{res} increases for all cavities with slow cooldown velocities
- Higher increase for one-cell cavities (0.7 to 0.9 nΩ)
  - initial R_{res} 1.3 to 1.6 nΩ
  - after slow cooldown R_{res} ~2.25 nΩ (~50%)
- Higher initial residual resistance for nine-cell cavity (2.29 nΩ)
  - increase to 2.56 nΩ (~12%)

Cavity:	**1AC3**	**1Z13**	**CAV00029**
R_{res} @ $v_{cd} \geq 0.01$ [nΩ]	1.35	1.56	2.29
R_{res} @ $v_{cd} < 0.01$ [nΩ]	2.26	2.25	2.56

CONCLUSION

- Completed Analysis Tool
- Cooldown velocity affects:
  the quality factor Q_0 reduced by ~12% (single cell cavity)
  the residual resistance R_{res} increases
- Accelerating gradient E_{acc} remains unaffected
- No impact on degradation due to quenching
- Needs to be further investigated
  - built more statistic
  - investigate behaviour of nine cell cavities further

REFERENCES

- [1] N. Walker et al. Performance in the vertical test of the 832 nine-cell 1.3 ghz cavities forthe european x-ray free electron laser. 2017.
- [2] H.Lierl et al. Conceptual Layout of the European X-FEL Linear Accelerator Cryogenic Supply 2004
- [3] Schematic of cryomodule and cooldown data at the curtesy of MKS
- [4] Cernox specifications. https://www.lakeshore.com/products/categories/specification/temperature-products/cryogenic-temperature-sensors/cernox.Accsesed on October 6, 2025.
- [5] Cernox™ resistance temperature sensors for high energy physics applica-tions. https://www.lakeshore.com/docs/default-source/product-downloads/application-notes/cernoxforhighenergy.pdf?sfvrsn=756b8bbf_4. Accsesed onOctober 6, 2025.