SRF Developments at the HIE ISOLDE Accelerating Structures Working Group

W. Venturini Delsolaro
on behalf of the ASWG:

L. Alberty, K. Artoos, S. Calatroni, O. Capatina, A. D'Elia, M. Elias, **N. M. Jecklin**, M. A. Fraser, Y. Kadi, P. Maesen, **I. Mondino**, E. Montesinos, A. Myazaki, G. Rosaz, K. Schirm, A. R. M. Sublet, M. Therasse, R. Valera, D. Valuch, **P. Zhang**

CATHI final review meeting
Barcelona, Spain, 22-26 September 2014

Contents

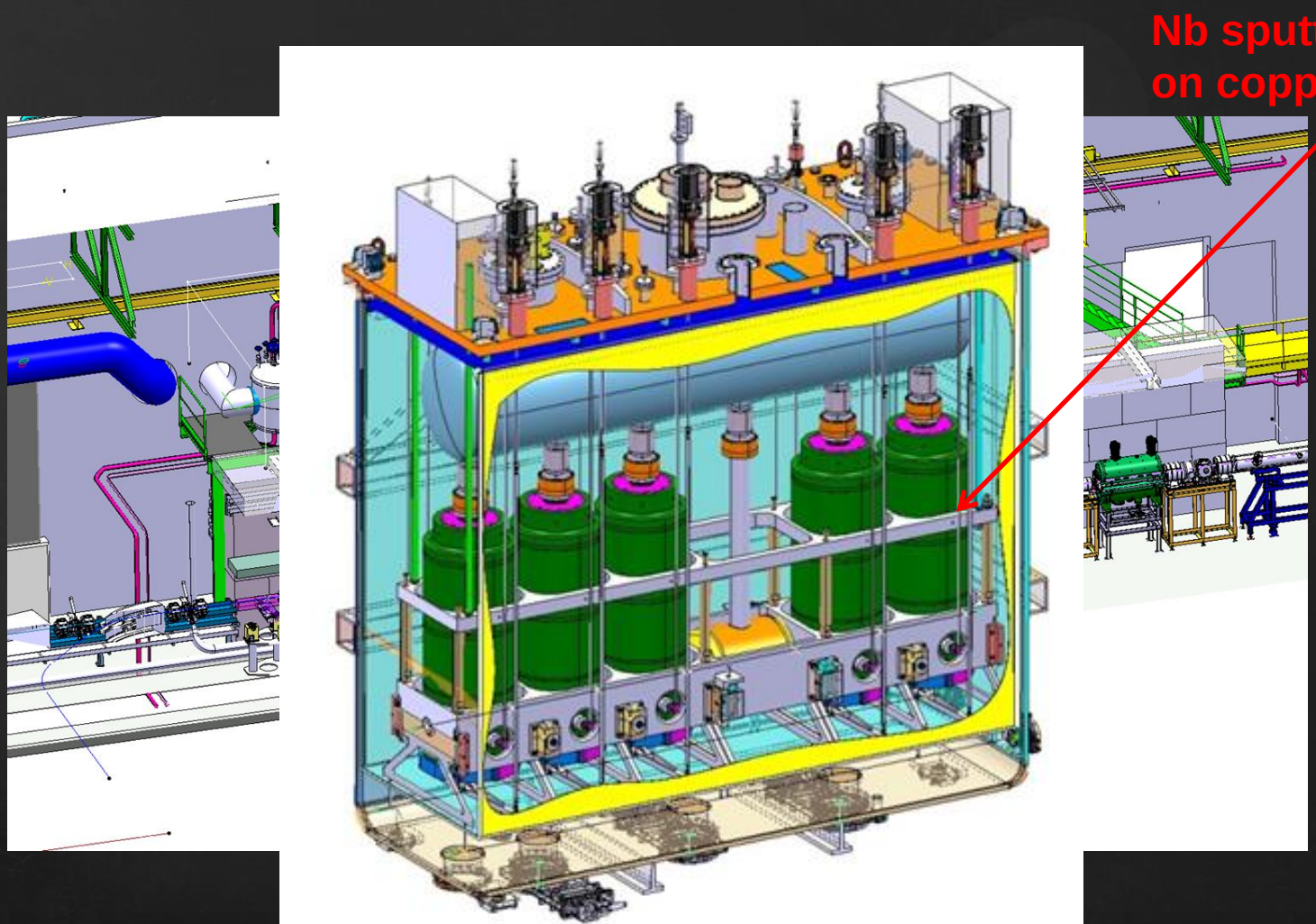
- ASWG mandate
- HIE ISOLDE cavity technical aspects:
  - QWR specifications
  - Cavity technologies
  - Development of Nb/Cu QWR for HIE ISOLDE
  - Coupling system
  - Tuning system
  - LLRF
- Conclusions

HIE-ISOLDE ASWG: facts and figures

- Design, technological choices and production
  - HIE ISOLDE Accelerating Cavities
  - Fundamental Coupler
  - Tuning System
- Multidisciplinary team: material science, RF and mechanical engineering, and more.
- **CATHI fellows first actors**
- Regular (now weekly) meetings
- Minutes and slides on EDMS

The HIE ISOLDE Cryomodues

Common vacuum concept - Actively cooled thermal shield-
Superconducting active elements: RF cavities and solenoid

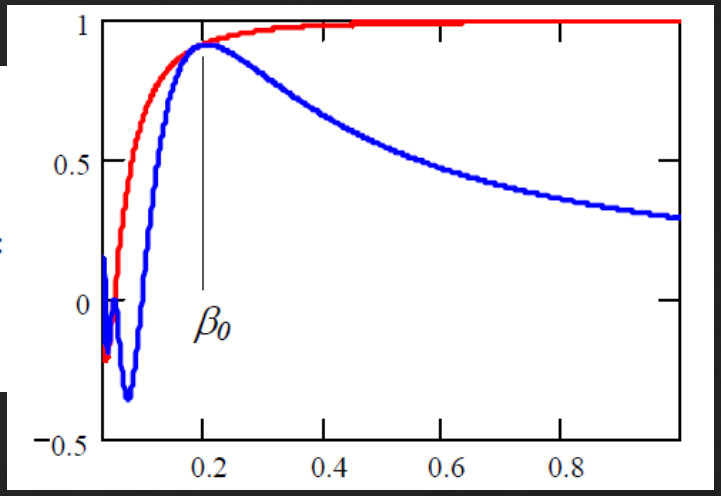


Why quarter wave resonators

At low particle velocities, effective acceleration depends on transit time

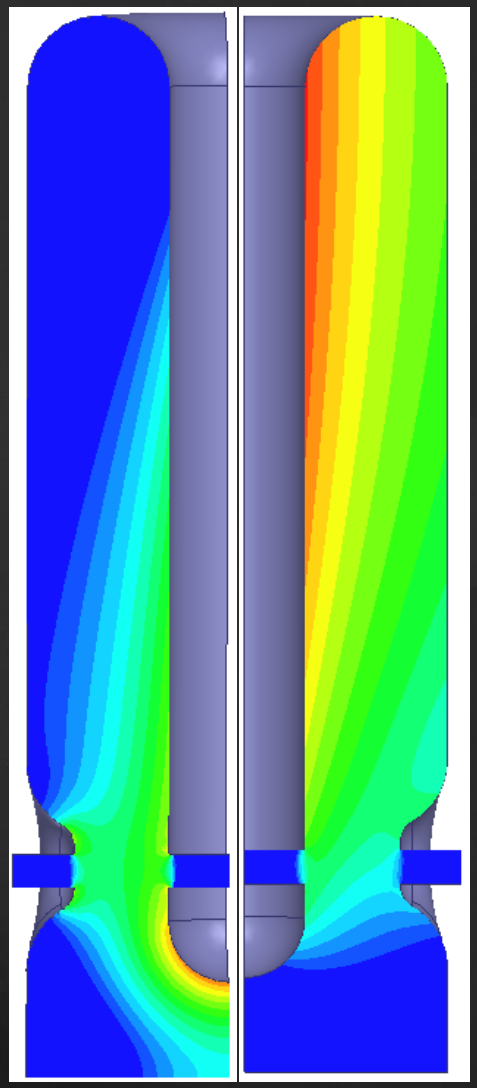
$$\Delta W_p = qE_a LT(\beta)\cos\varphi$$

$$T(\beta) =$$



- Low frequency improves the TTF
- Multi (two) gap structure → TTF curve with a maximum (optimum beta)
- Quarter wave resonators have broader TTF(β) curves (larger energy acceptance); relatively favourable field ratios for a low beta structure, and high frequency of the lowest mechanical mode
- Low frequency → low BCS surface resistance→ 4.2 K operation

High beta QWR design (electromagnetic)



HIE ISOLDE	Baseline†	New*
f_0 at 4.5 K [MHz]	101.28	101.28
β_{opt} [%]	10.86	10.88
TTF at β_{opt}	0.9	0.9
R/Q [Ω] (incl. TTF)	554	556
E_p/E_{acc}	**5.5**	**5.0**
H_p/E_{acc} [G/(MV/m)]	95.4	95.3
U/E^2_{acc} [mJ/(MV/m)^2]	208	207
$G=R_sQ$ [Ω]	30.7	30.8
P_{diss} @ 6 MV/m [W]	**10**	**10**
P_{diss} on bottom plate [W]	**0.0035**	**0.0018**

†Original tuning plate *Simplified tuning plate

Ref. Proceedings of SRF2009, p. 609

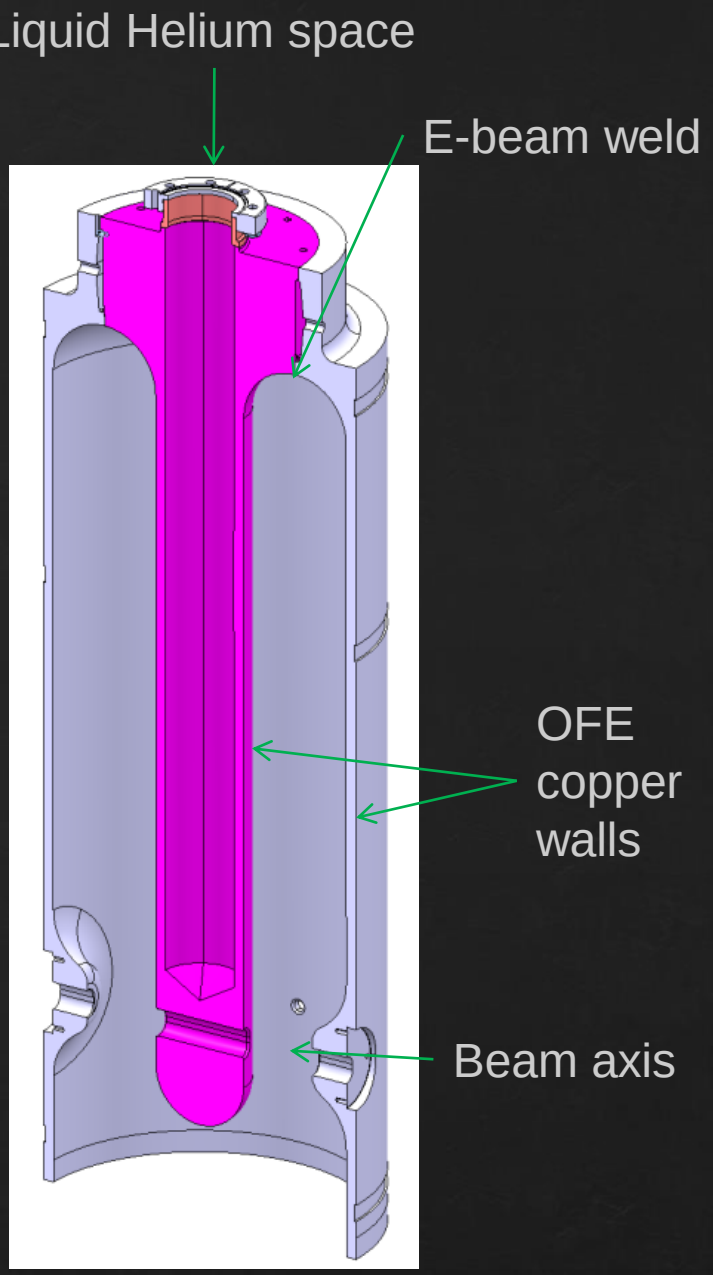
Choice of cavity technology

Superconducting option

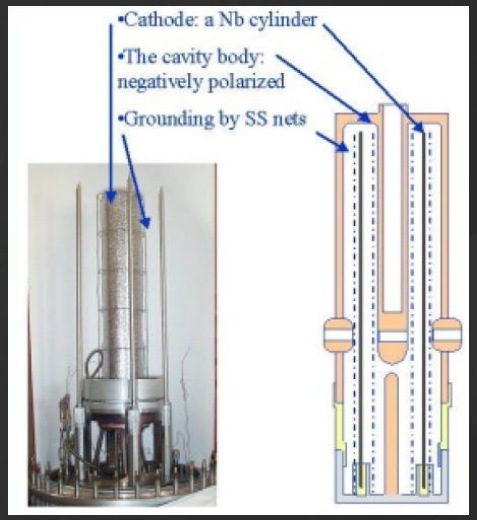
- High Q (low power dissipation)
- Cryogenics
- High CW fields (30 MV/m peak)
- Possible field emission, X rays

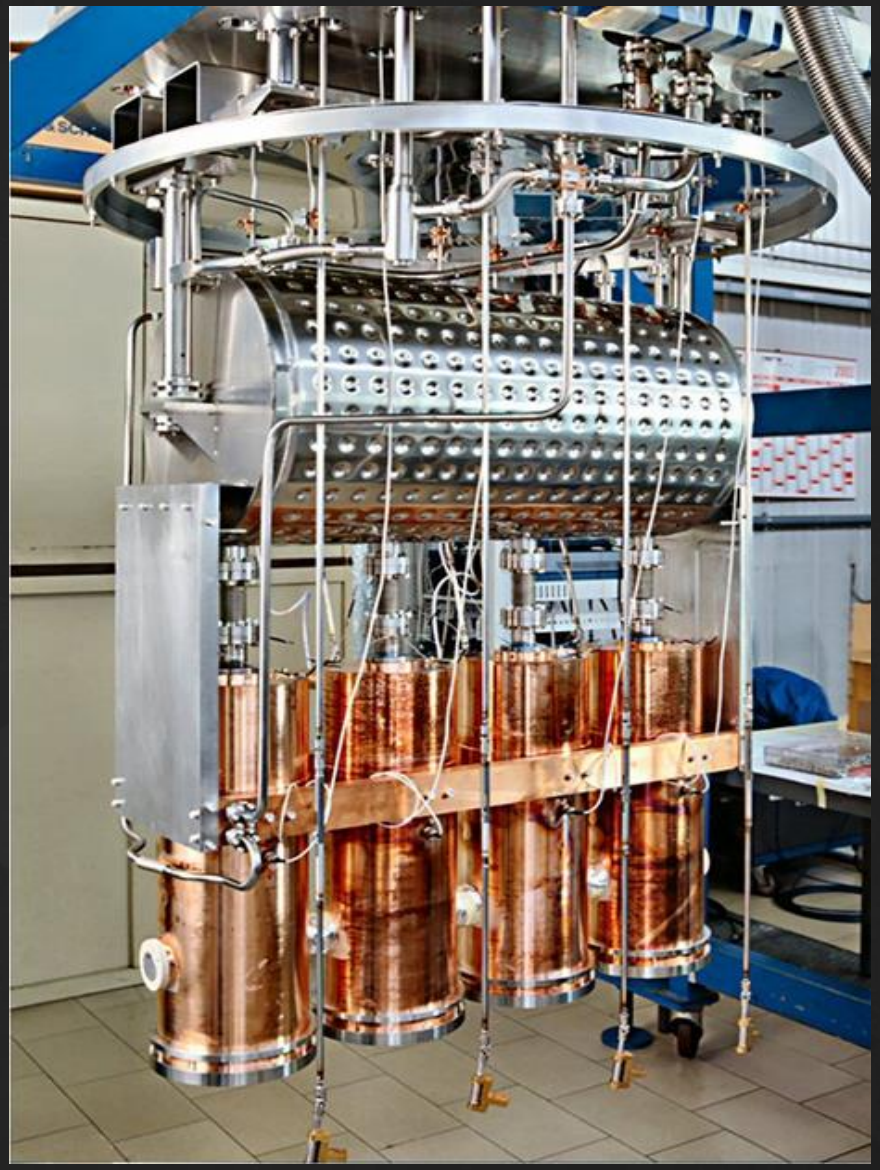
Niobium sputtering on copper

- Thermal stability
- Mechanical stability→ less sensitive to He pressure fluctuations and to mechanical vibrations→ Low RF power
- Less sensitive to magnetic fields→ no need of shielding the cryostat
- Potentially cheaper (especially for large series)
- Possible to recycle substrates



The ALPI experience: over 50 Nb/Cu QWR made at INFN -LNL installed between 1999 and 2003





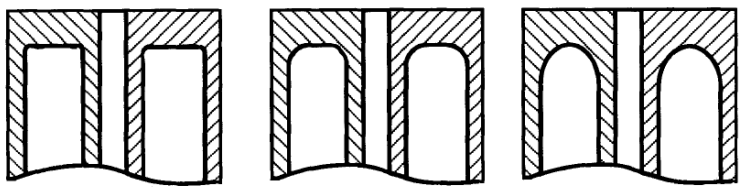
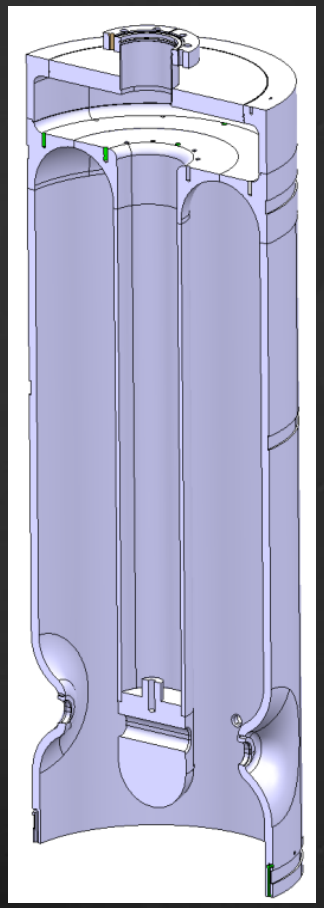


Fig. 6. Detail of resonator geometry: a) old model with curvature radius of 10 mm; b) modifyed model with curvature radius of 20 mm; c) definitive model with curvature radius of 30 mm.

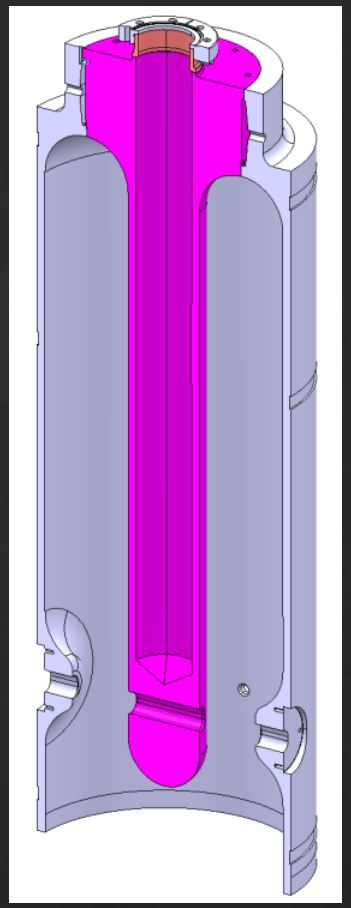
Evolution of resonator geometry
(from *V. Palmieri, V. L. Ruzinov, S. Stark, et al; Proceedings of the 6th Workshop on RF superconductivity, 1993)*

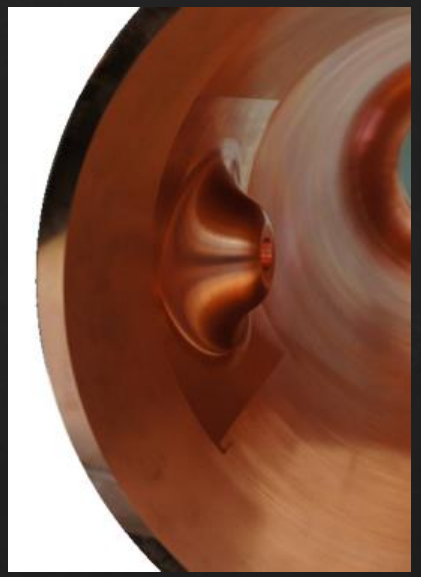
High beta QWR design (mechanical)

Version 1



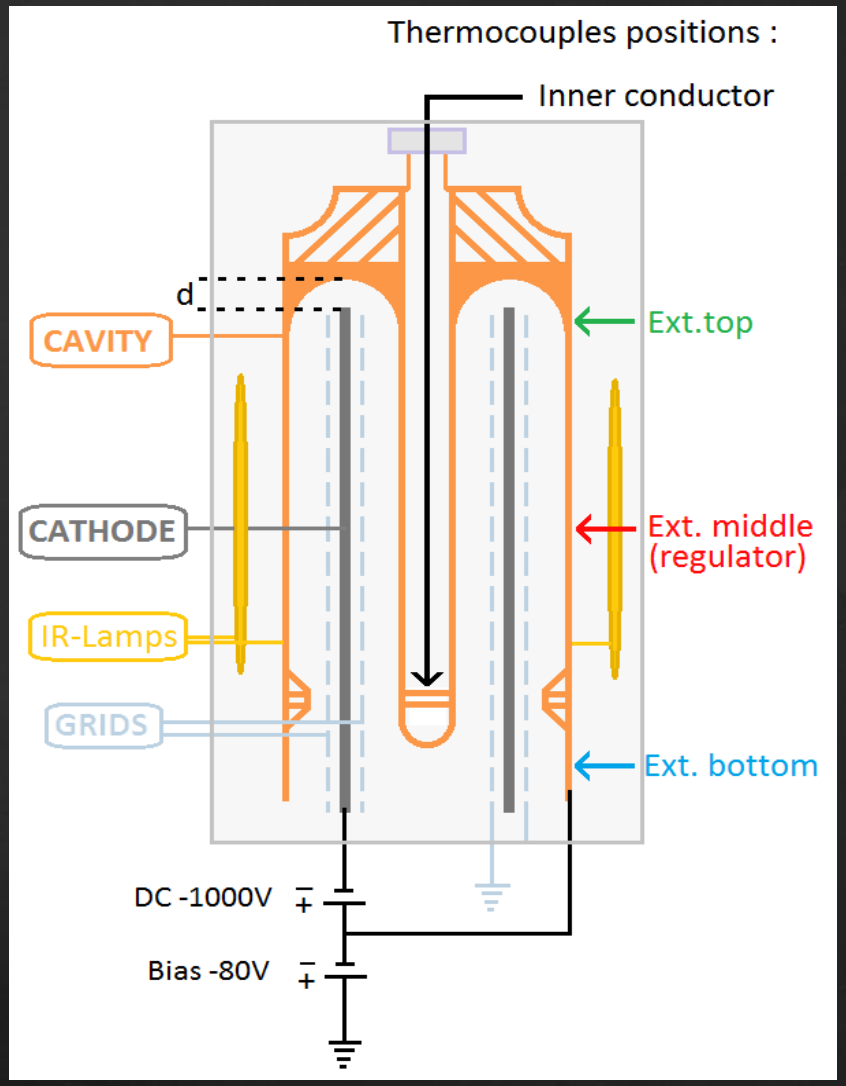
Version 2



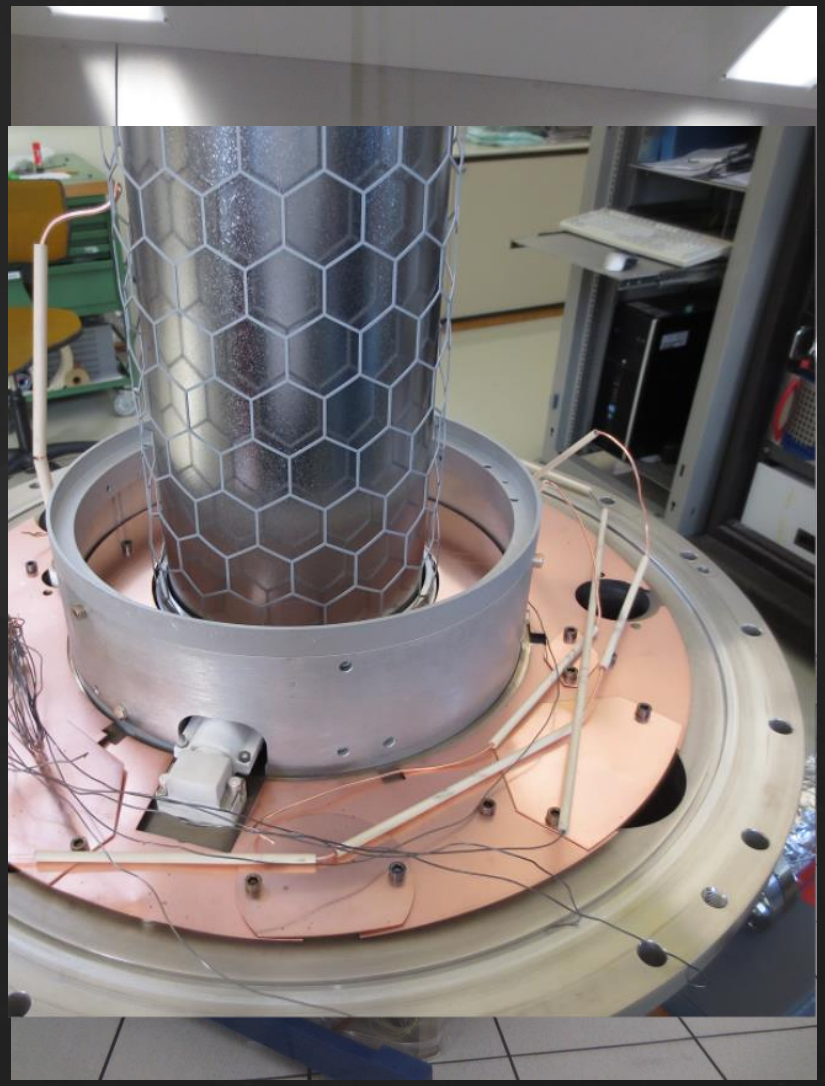


Bias diode sputtering system

Schematics



System assembly in ISO 5 clean room



Power dissipation, surface resistance

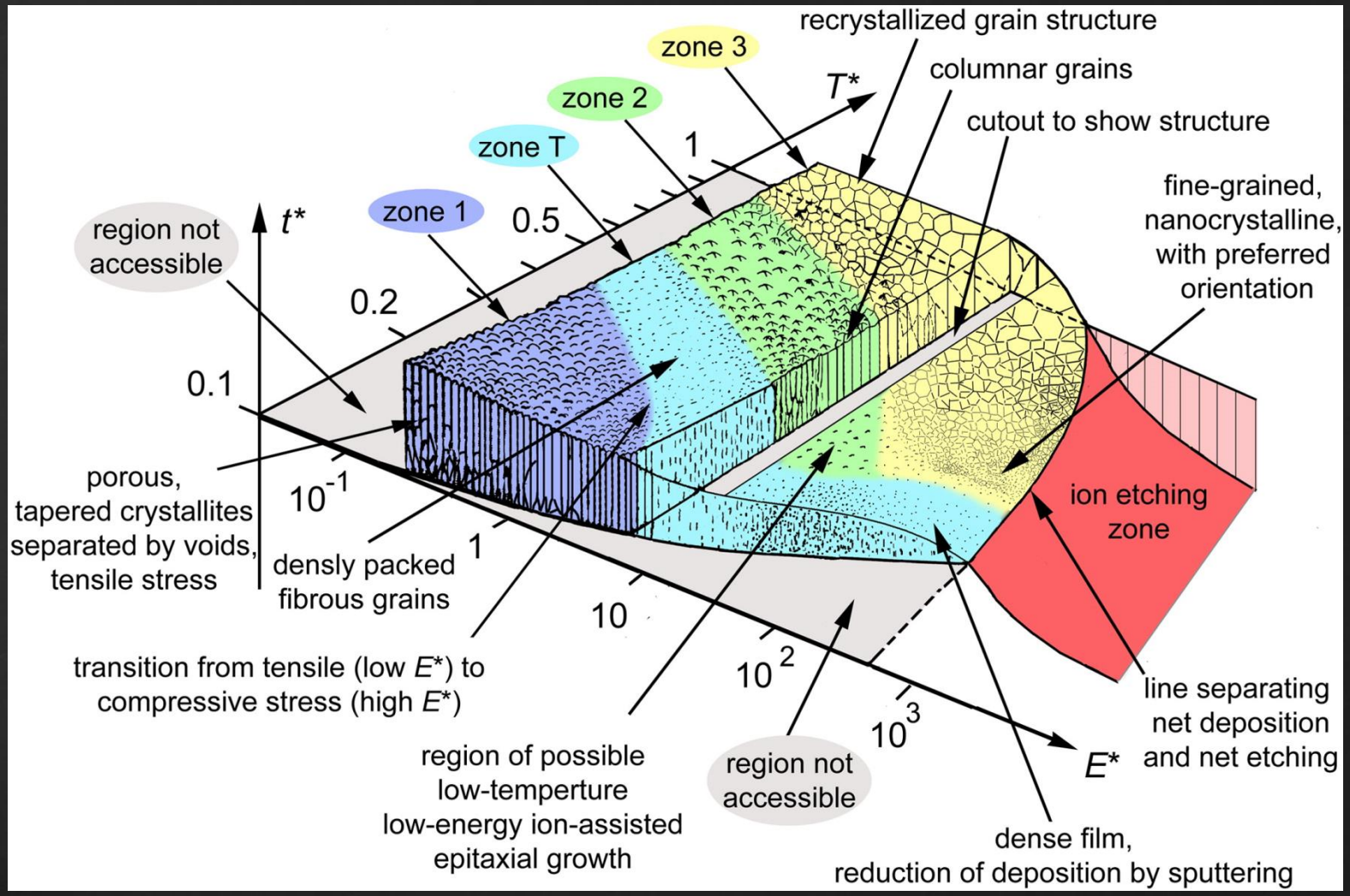
$$P_c = \frac{1}{2} R_s \int H^2 ds \qquad Q_0 = \frac{\omega U}{P_c} = \frac{\Gamma}{R_s}$$

$$R_s = RB_{CS} + Rr_{es} \qquad R_{BCS} = \frac{A\omega^2}{T} \exp\left(-\frac{\Delta}{k_B T}\right)$$

HIE ISOLDE low beta cavity:
R_{BCS} at 4.2 K and 101.28 MHz < 10% of total R_s

R_{res} is related to the "real" surface: defects, oxides, etc.

Thin film growth: structure zone models



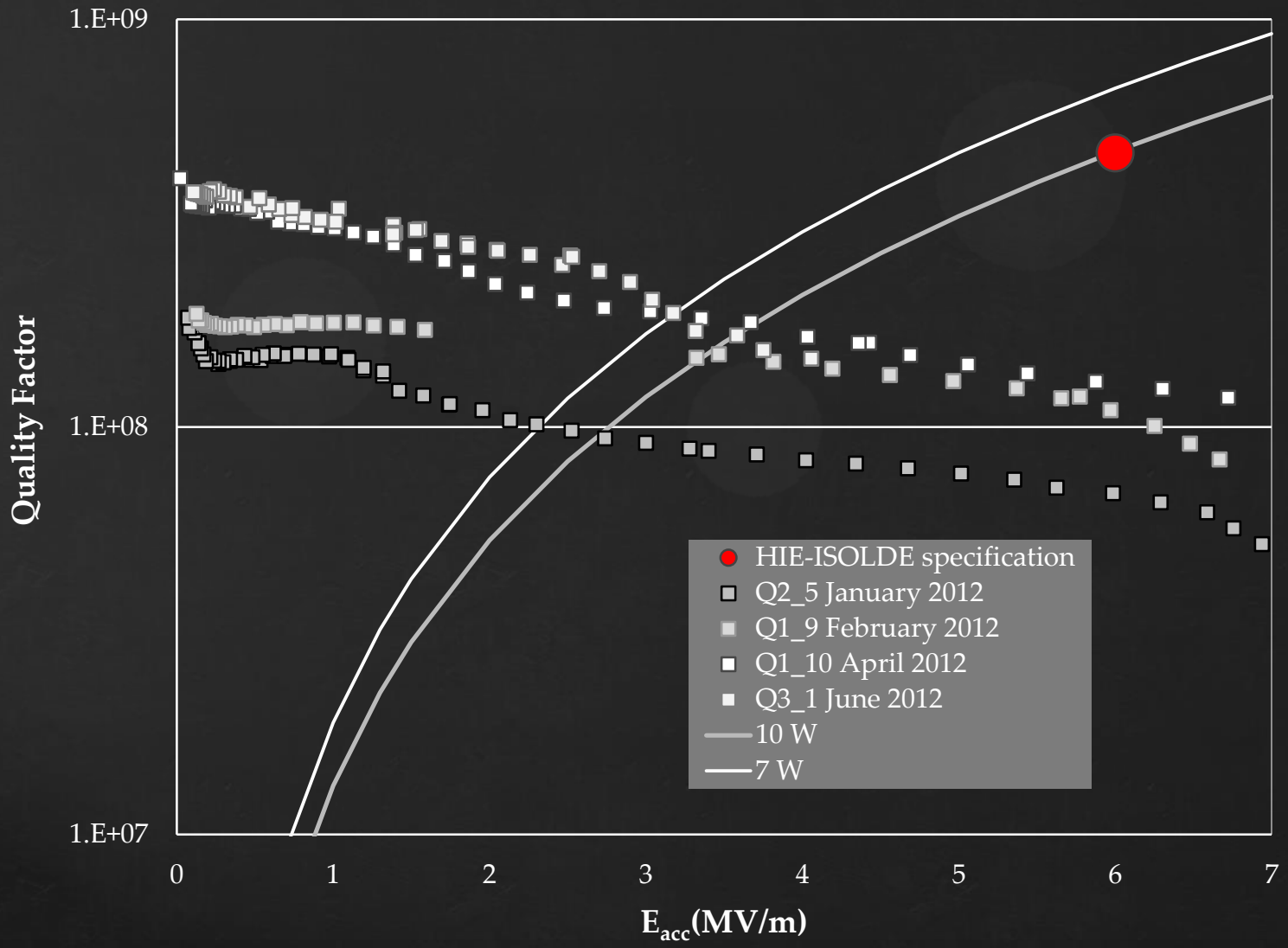
A. Anders, Thin Solid Films, Volume 518, Issue 15, 31 May 2010, Pages 4087–4090

Roadmap of developments (2011-2013)

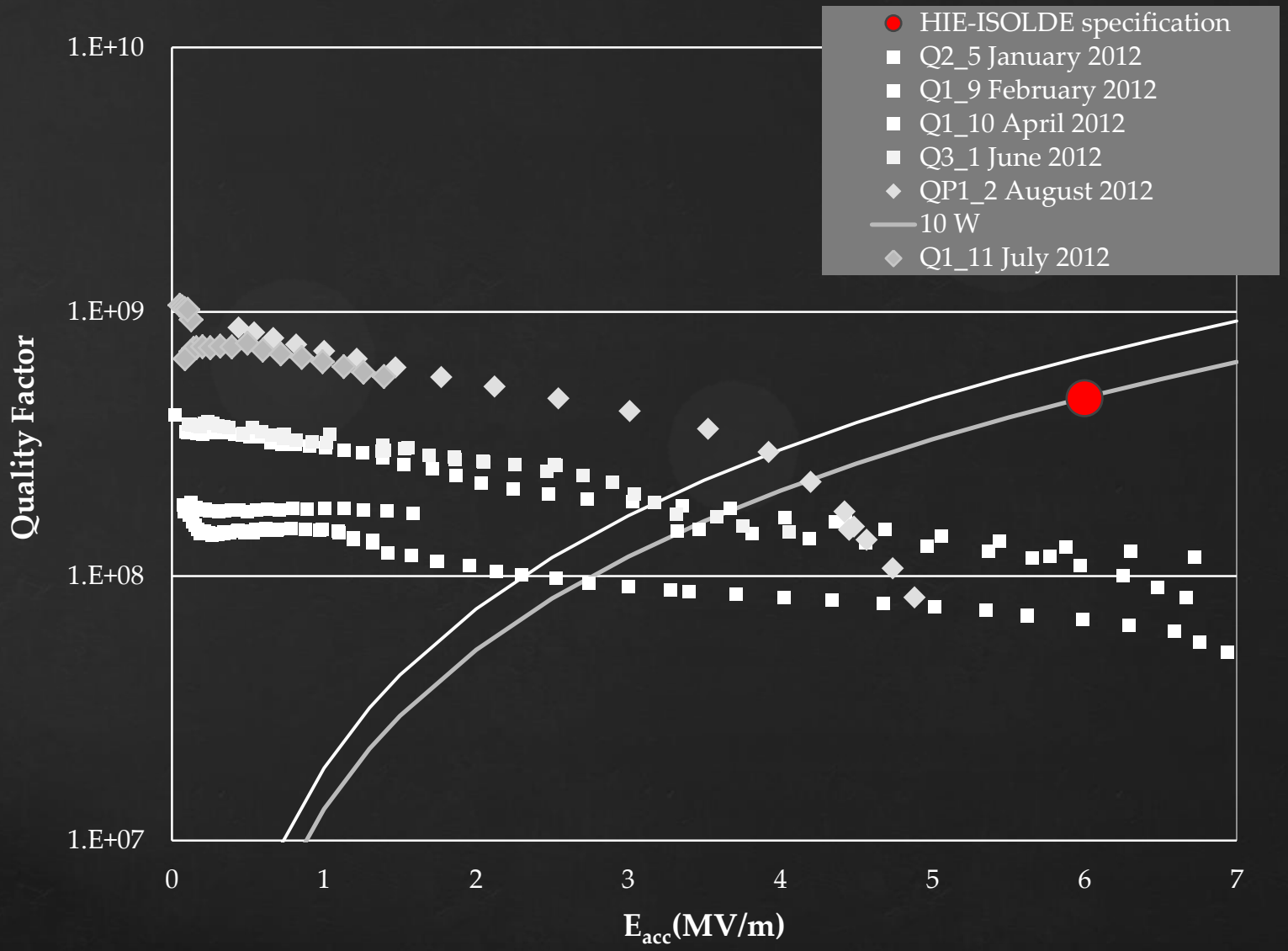
Strong development program focused on bias diode sputtering method. Main steps:

- Increasing baking and coating temperatures
- Increasing sputtering power (global deposition rate)
- Coating in steps
- Sputtering gas, venting gas
- Global film thickness
- Local film thickness

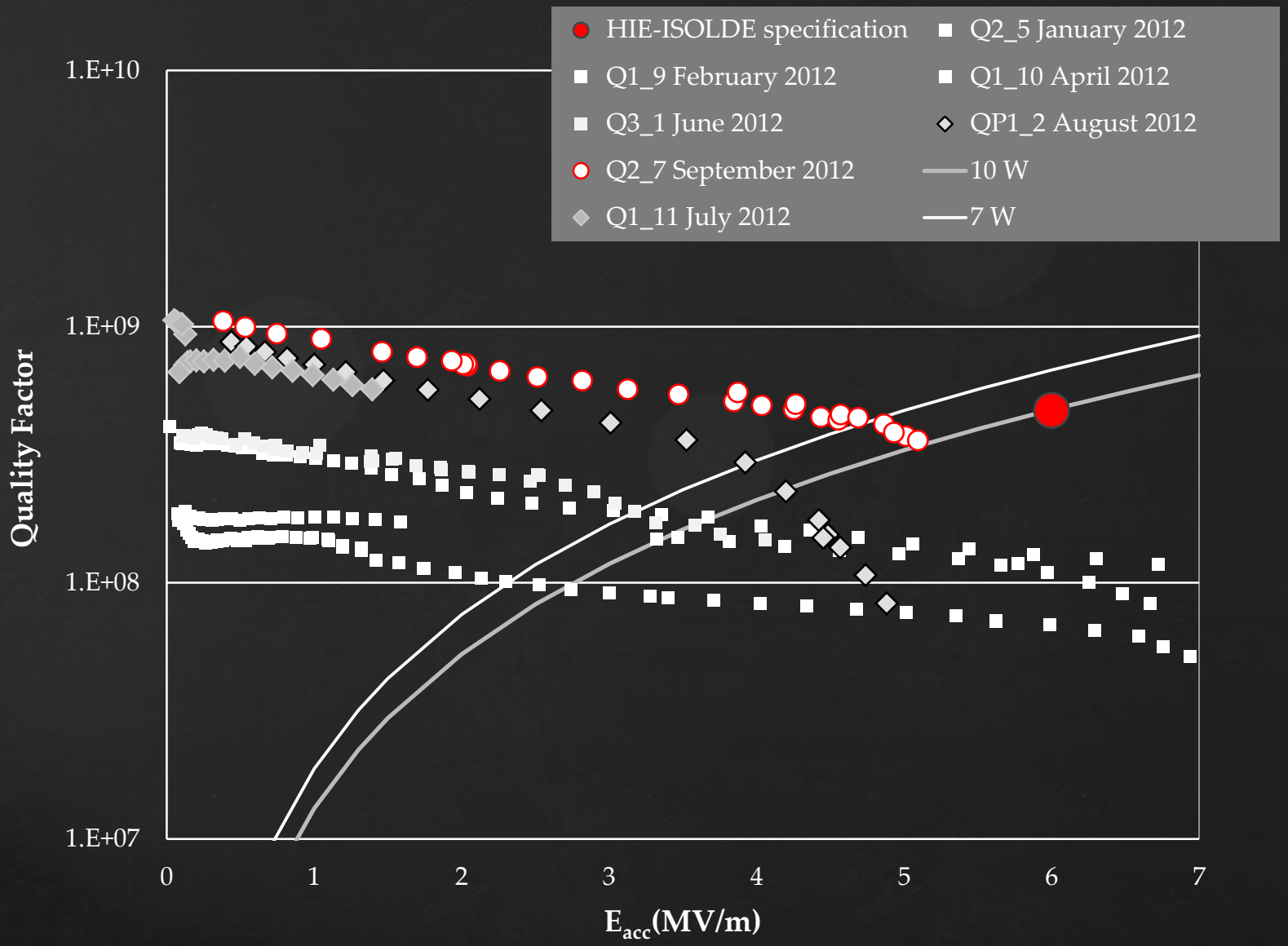
Increasing coating temperature, $T_{(bake\ out)} < T_{(coating)} \rightarrow 600\ °C$



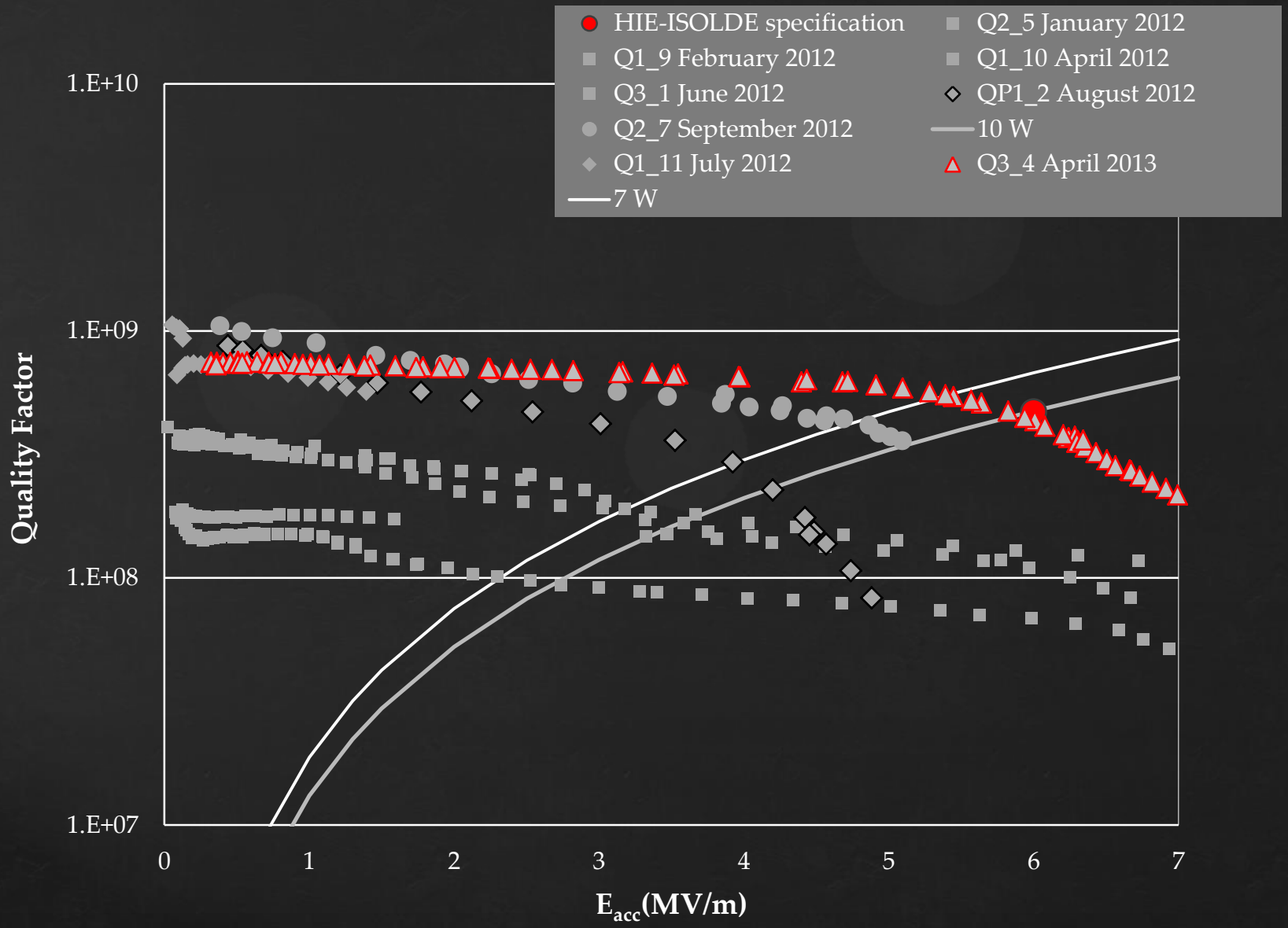
$T_{(bake\ out)} > T_{(coating)}$, higher sputtering power (layers), change of gases: Kr, dry air → Ar, N_2



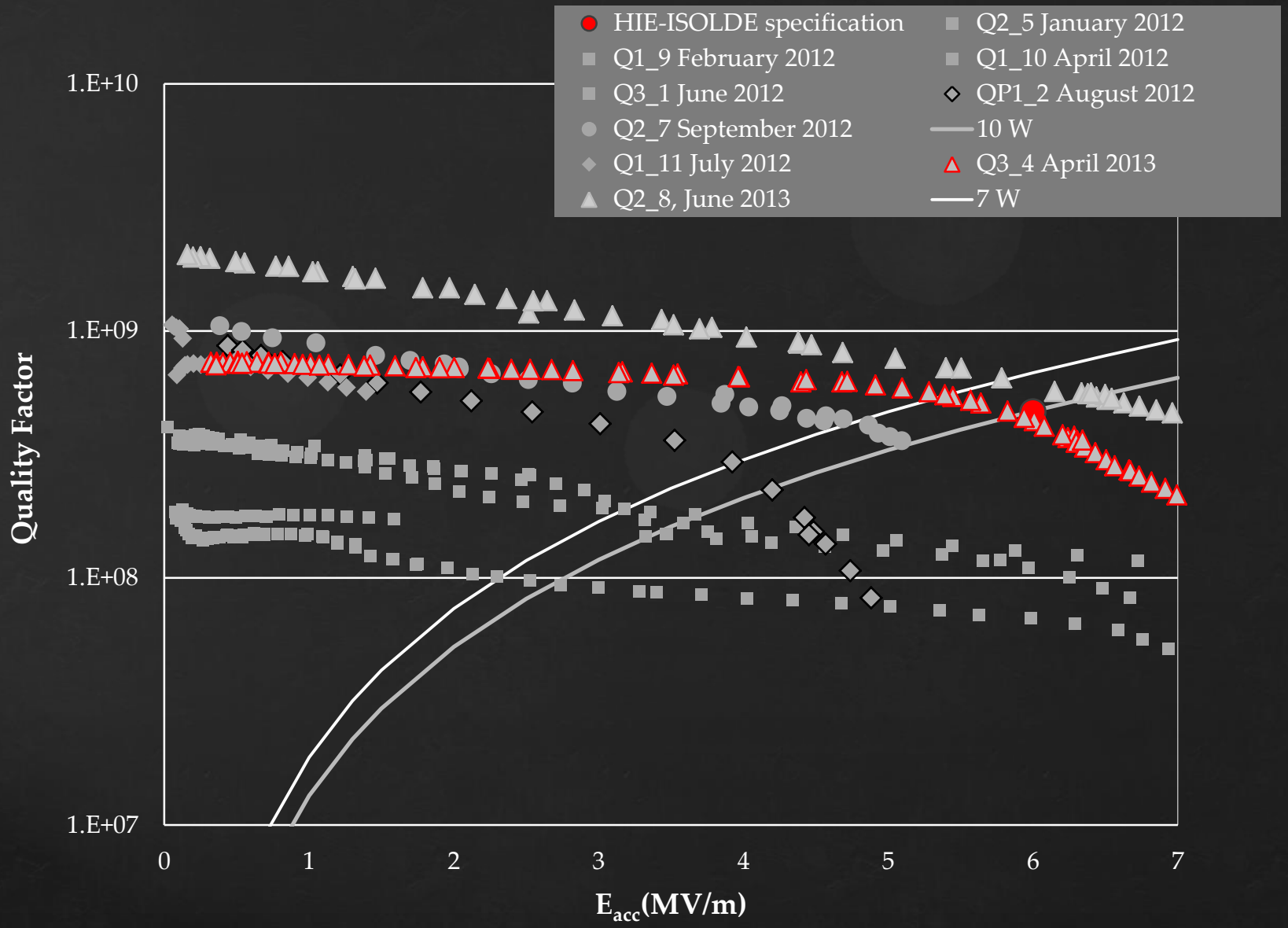
Increasing global Nb thickness by 25%



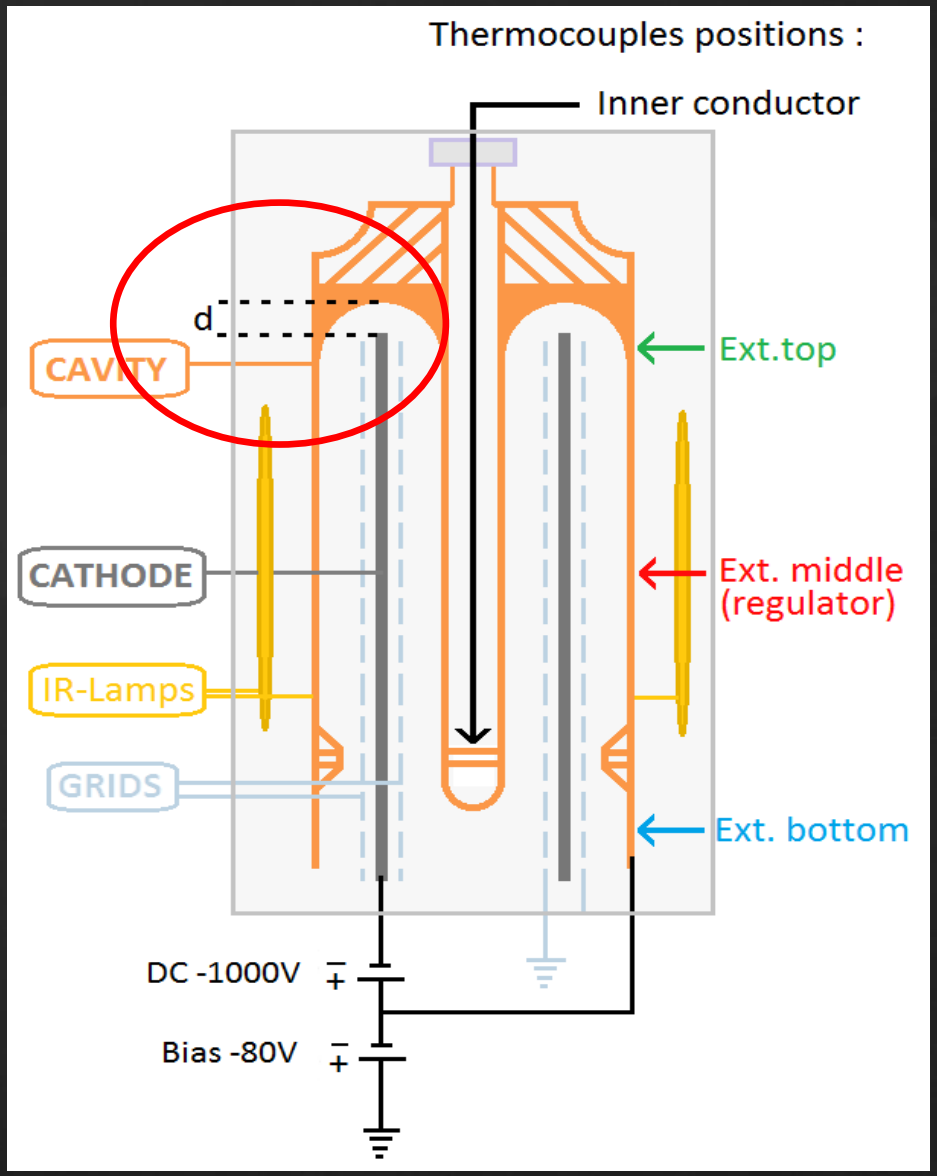
Reduced “top gap” length from 52 mm down to 32 mm



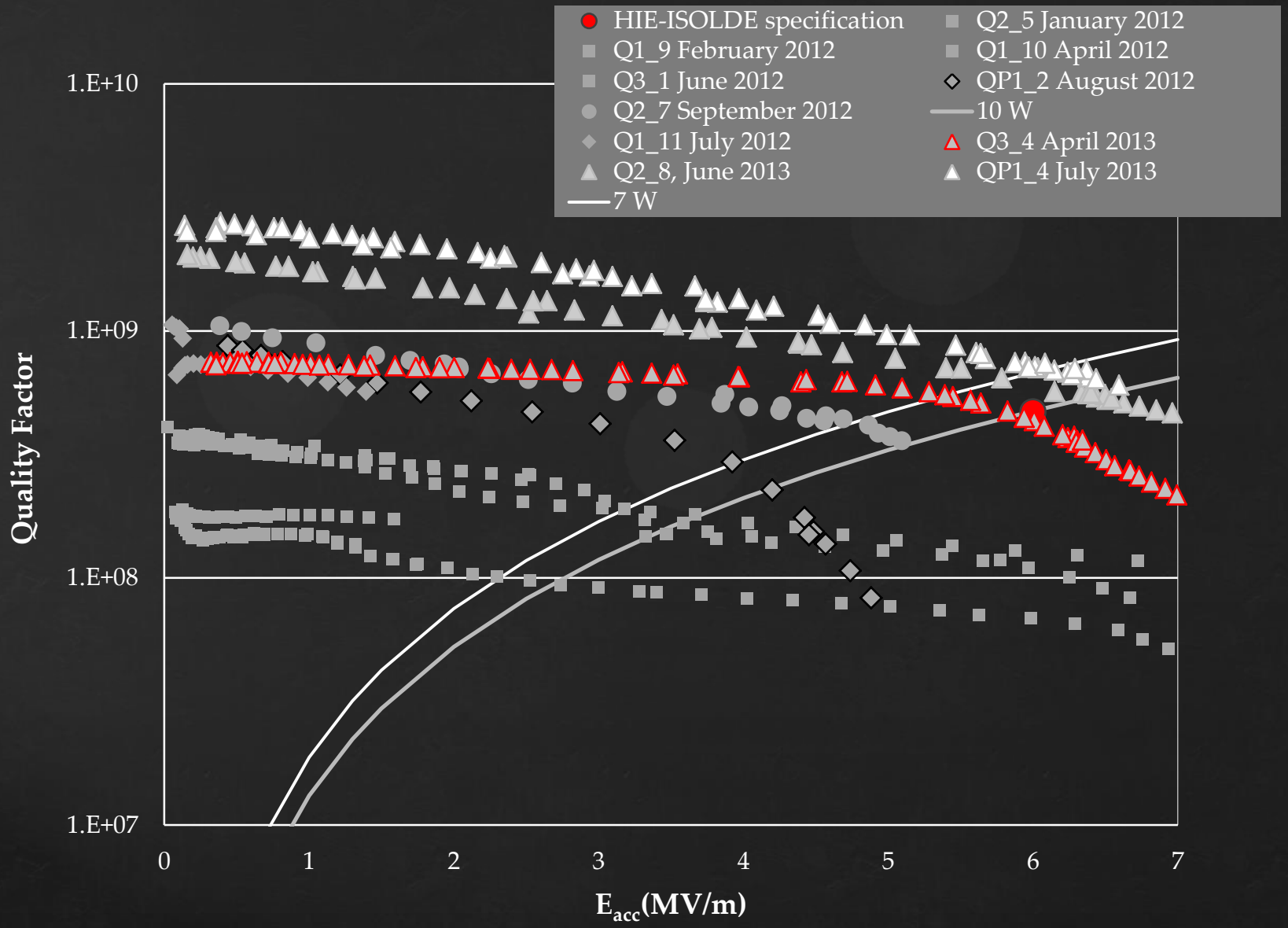
Same parameters on a 20 mm shorter substrate



Scaling the “top-gap” length

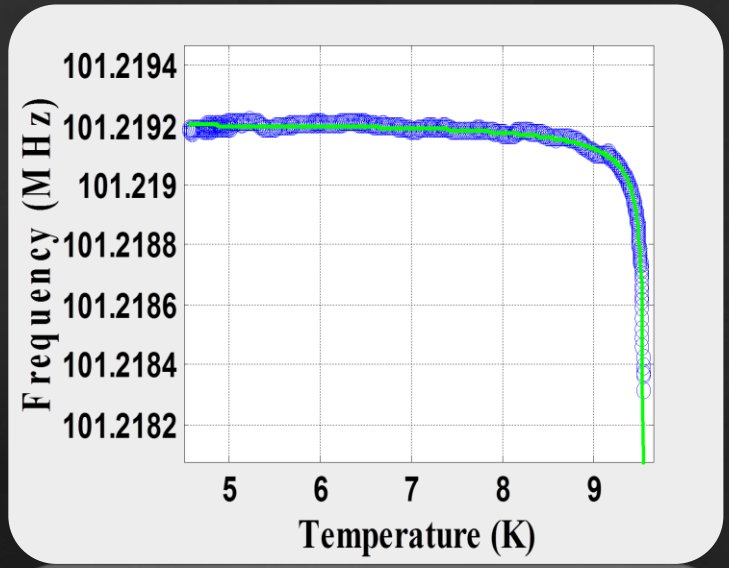


Top gap distance reduced to 22 mm



Average RRR extracted from $f_{res}(T)$ measurements

λ_0 =51±3 nm
T_c=9.55817±4e-5 K
Freq=101219201±3.5 Hz
mfp =64±14 nm
ϱ = (0.6±0.1) μΩ*cm
RRR =26±5.5



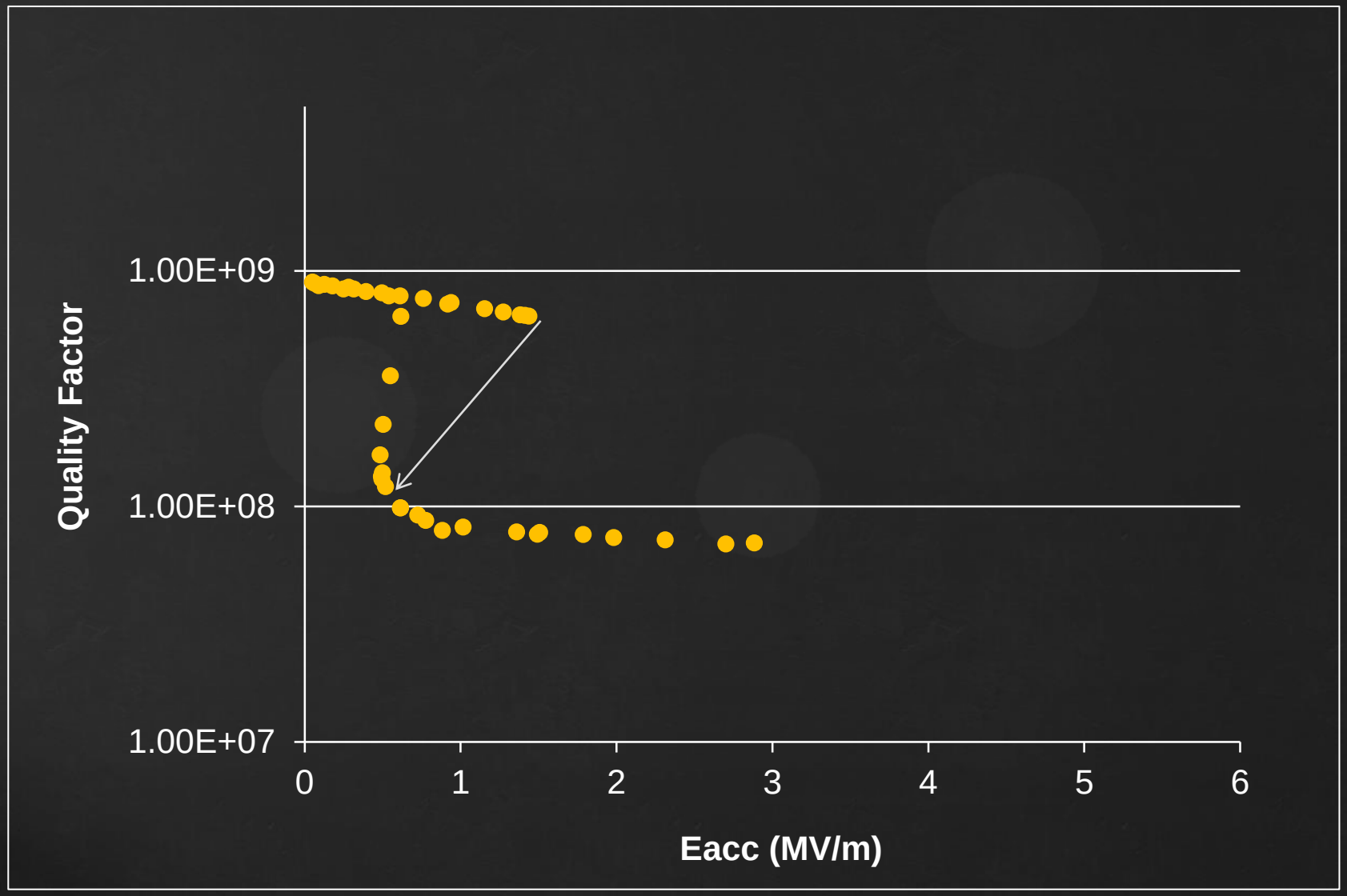
Coating test	λ_0 (nm)	RRR
Q2_3 April 2011	188	1.9
Q1_5 June 2011	83	6.8
Q1_10 Feb. 2012	62.3	13.5
Q2_8 April 2013	50.7	26.4
Q3_4 March 2013	45.7	41. 8

Surface quality of the inner conductor tip → field emission

Central electrode: 20 mm diameter, at earth potential

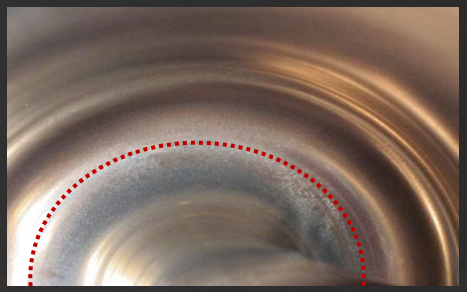
No counter electrode

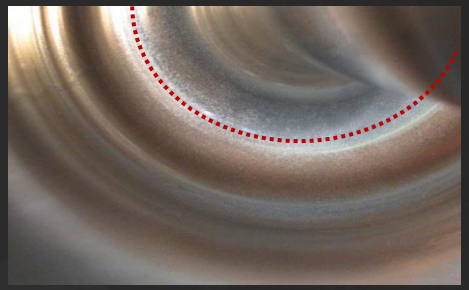
Q switches

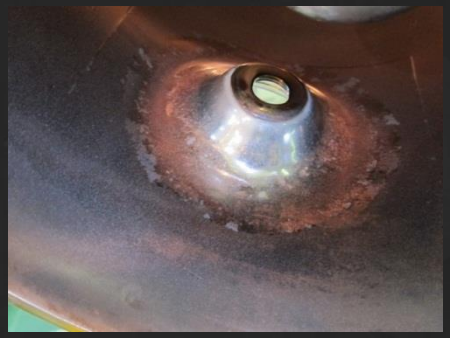


Investigating thickness/adhesion by step-stripping

Q1_11: Pictures after 15’ stripping + 100bar rinsing
Cavity top (---- = welding ring)

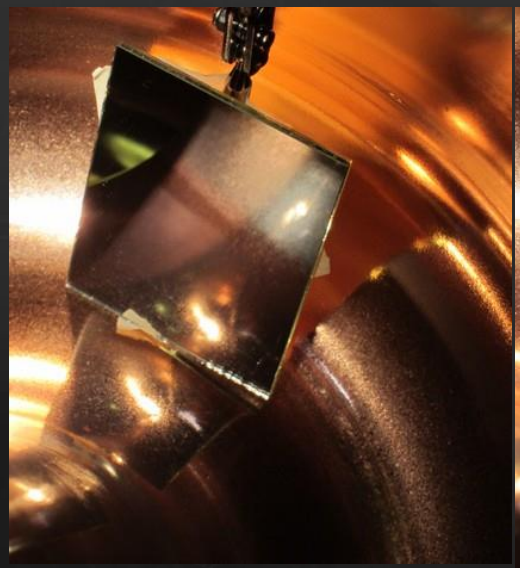


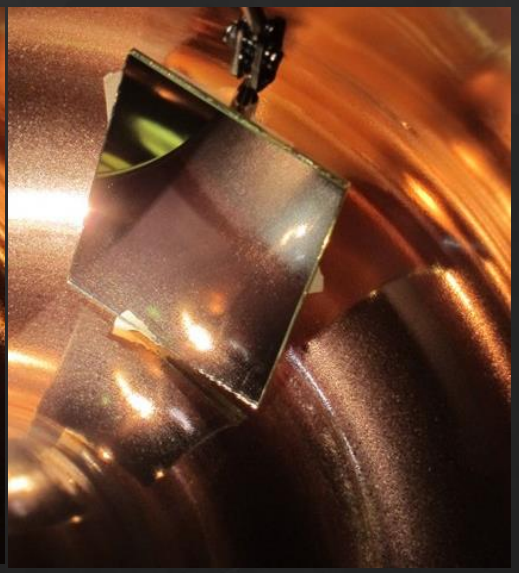




Confirmed and integrated the information on thickness profile from beta-scope and sample measurements

Pictures after 15’ +15’ stripping + 100bar rinsing



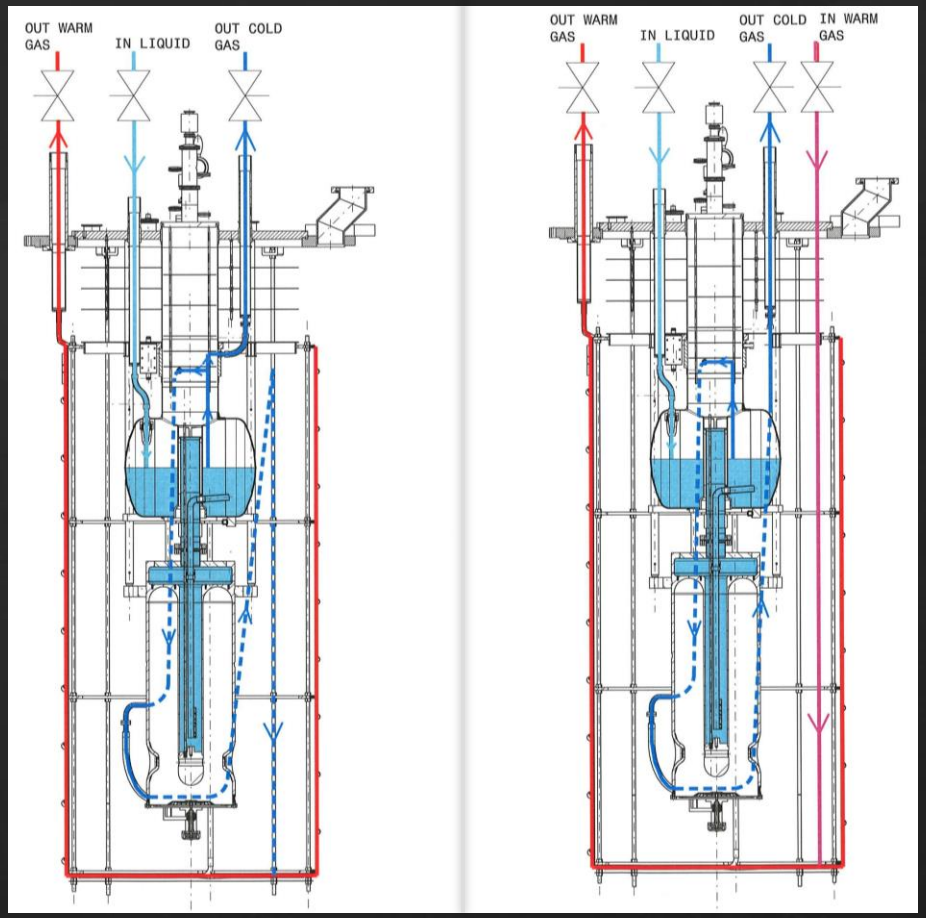


Cooling circuits: series vs. parallel

Phase I Test cryostat Phase II Test cryostat

Series:

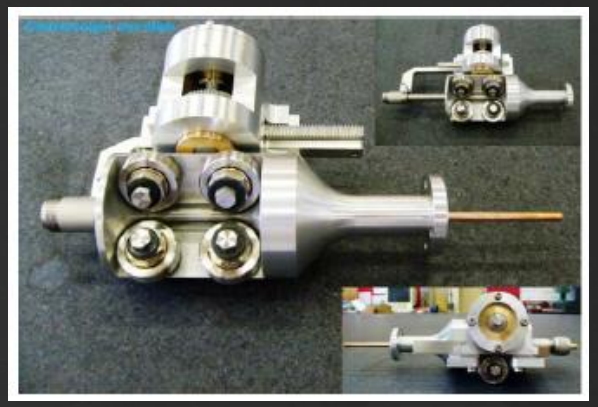
1. The He tank is cooled down
2. The cold gas is extracted and used to thermalize the RF cable
3. The gas is then directed to the thermal screen

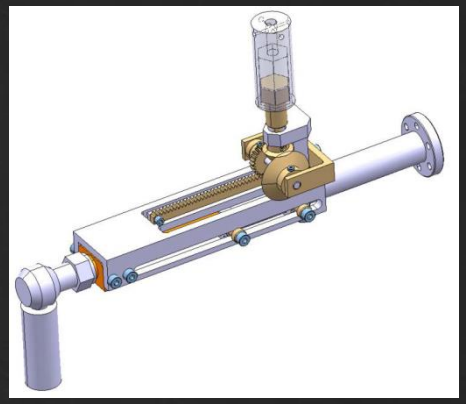


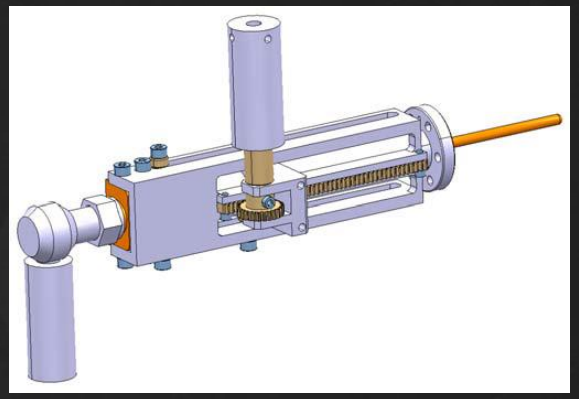
Parallel:

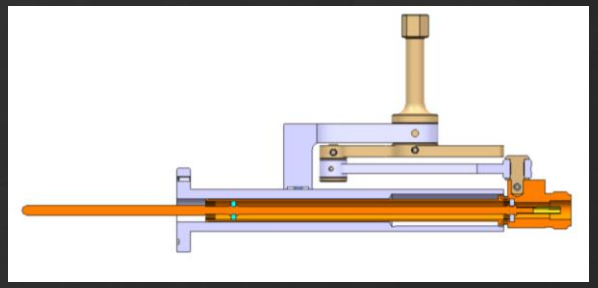
1. The He tank is cooled down
2. The cold gas is directed to thermalize the RF cable and extracted
3. An independent line feeds the thermal screen

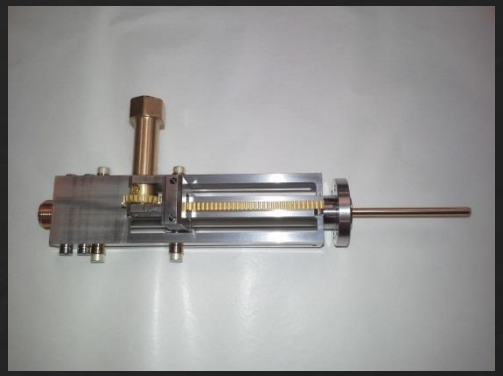
Coupling system evolution

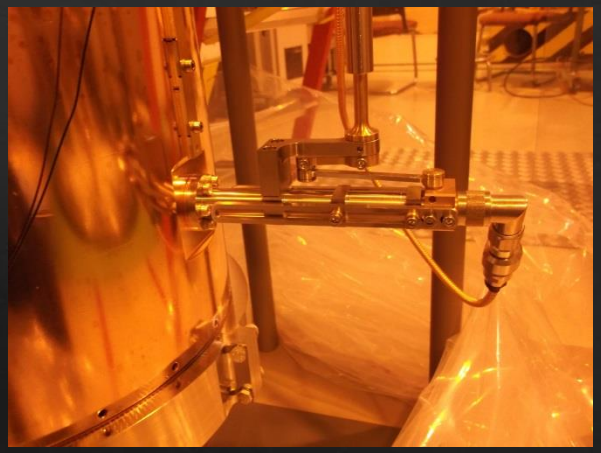


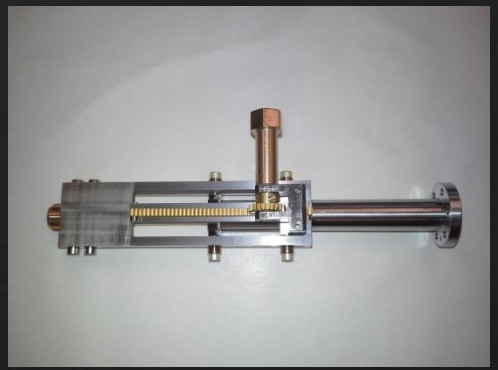




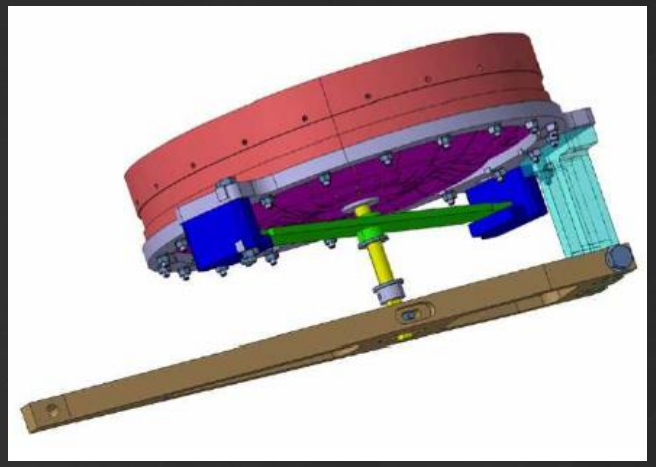


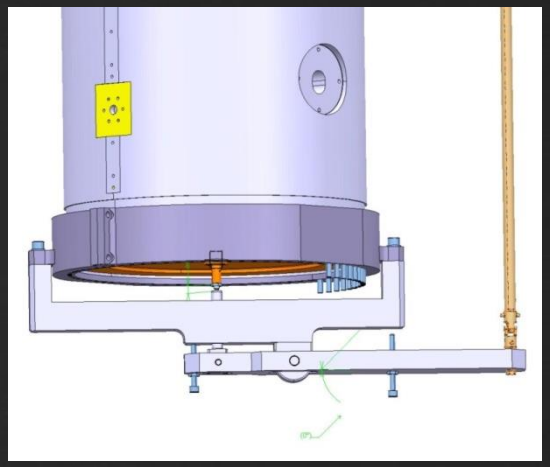


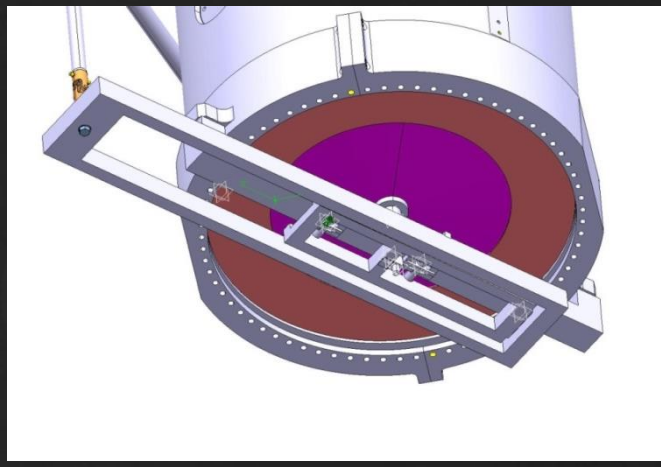


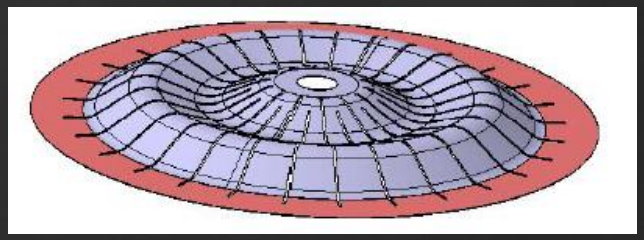


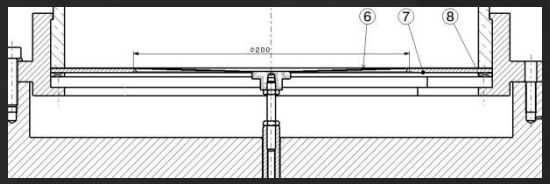
Tuning system evolution (plates and actuators)

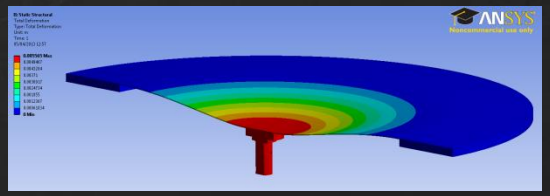




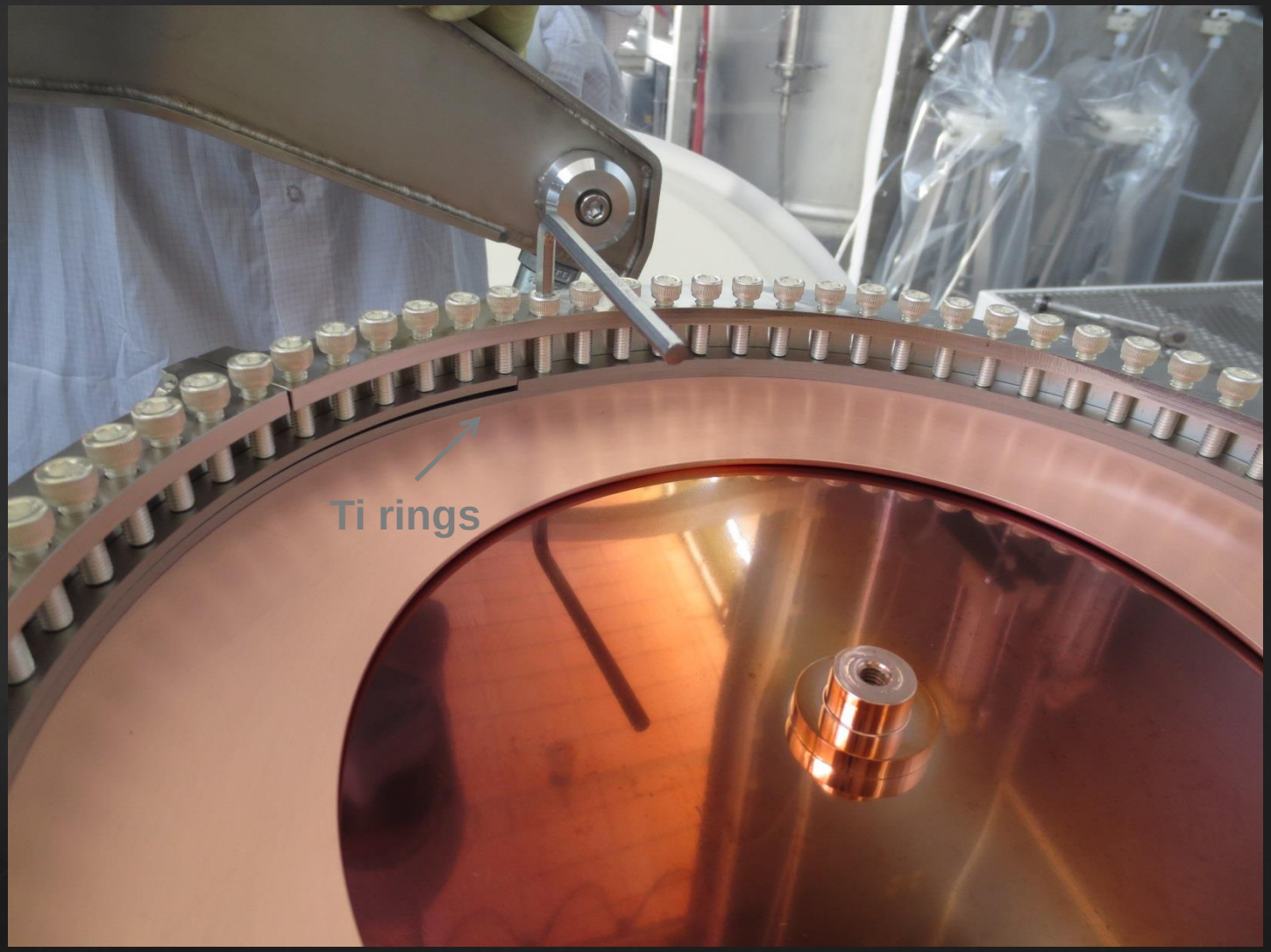




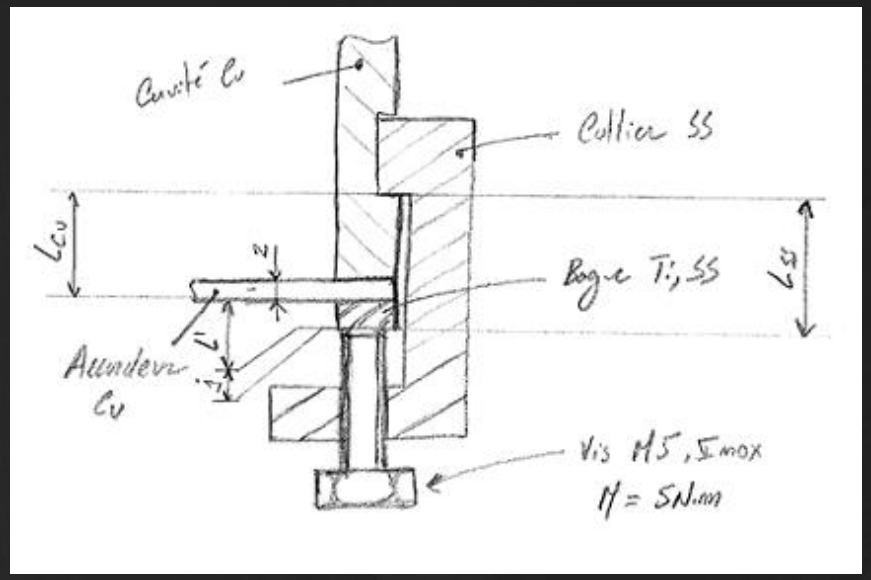




Tuning plate is fixed with 72 M6 screws closed at 5 Nm and acting on Ti rings



Pondering on the RF contact at cold…



GEOMETRIE

Lcu := 17mm

LL := 3mm

Lss := Lcu + LL = 20·mm

BAGUE TITANE

Jti := −Lss·AISI304Integral + Lcu·OFECuintegral + LL·Ti6Al4VIntegral = 1.086×10^{-3}·mm

BAGUE INOX

Jss := −Lss·AISI304Integral + Lcu·OFECuintegral + LL·AISI304Integral = 4.84×10^{-3}·mm

CALCUL DE LA DEFORMATION ELASTIQUE (COMPRESSION) À CHAUD

ΔL = Faxial x Σ (lo/EA)

VIS = M6 (72x)

$$Abague := \pi \cdot \left[\frac{(320mm)^2 - (300mm)^2}{4} \right] = 9.739 \times 10^{3} \cdot mm^2$$

Ecu := $105 \cdot 10^{3}$MPa = 1.05×10^{11} Pa

Ess := $200 \cdot 10^{3}$MPa = 2×10^{11} Pa

Eti := $110 \cdot 10^{3}$MPa = 1.1×10^{11} Pa

Faxial := 72·6900N = 4.968×10^{5} N

Avis := $72 \cdot 17.9mm^2$ = $1.289 \times 10^{3} \cdot mm^2$

Lvis := 49mm − Lss = 29·mm

BAGUE TITANE

$$\Delta Lti := Faxial \cdot \left(\frac{Lvis}{Ess \cdot Avis} + \frac{LL}{Eti \cdot Abague} + \frac{Lcu}{Ecu \cdot Abague} \right) = 0.066 \cdot mm$$

BAGUE INOX

$$\Delta Lss := Faxial \cdot \left(\frac{Lvis}{Ess \cdot Avis} + \frac{LL}{Ess \cdot Abague} + \frac{Lcu}{Ecu \cdot Abague} \right) = 0.065 \cdot mm$$

CALCUL DU RELACHEMENT À FROID

Les pertes de deformation (en compression) sont equivalentes aux pertes de serrage

ΔLtifroid := ΔLti − Jti = 0.064·mm $\quad \frac{\Delta Ltifroid}{\Delta Lti} = 98.343 \cdot \%$

ΔLssfroid := ΔLss − Jss = 0.06·mm $\quad \frac{\Delta Lssfroid}{\Delta Lss} = 92.545 \cdot \%$

% du serrage à chaud qui reste à froid

Si 2 bagues sont installées (LL=6mm): $\frac{\Delta Ltifroid}{\Delta Lti} = 104.362\,\%$

CONCLUSIONS: $\frac{\Delta Lssfroid}{\Delta Lss} = 91.921\,\%$

Car la déformation par compression élastique des composants en série (~60um) soumis à la charge des vis est toujours plus importante que la contraction thermique (1-5um), le contact est toujours assuré, soit avec la bague en inox, soit avec la bague en titane.

Avec: -1 bague en titane (t=3mm), la pression de contact reste pratiquement la même (98%);

-2 bagues en titane (t=6mm), la pression de contact augmente de 4%;

-1 bague en inox (t=3mm), la pression de contact reste à 92% de la valeur initial;

-2 bagues en inox (t=6mm), la pression de contact reste aussi à env. 92%;

Remaining issue in 2014 Cavity Tuning

Available tuning range: 40 kHz

Statistics of warm to cold shift was known

Strategy to cut the cavity at reception

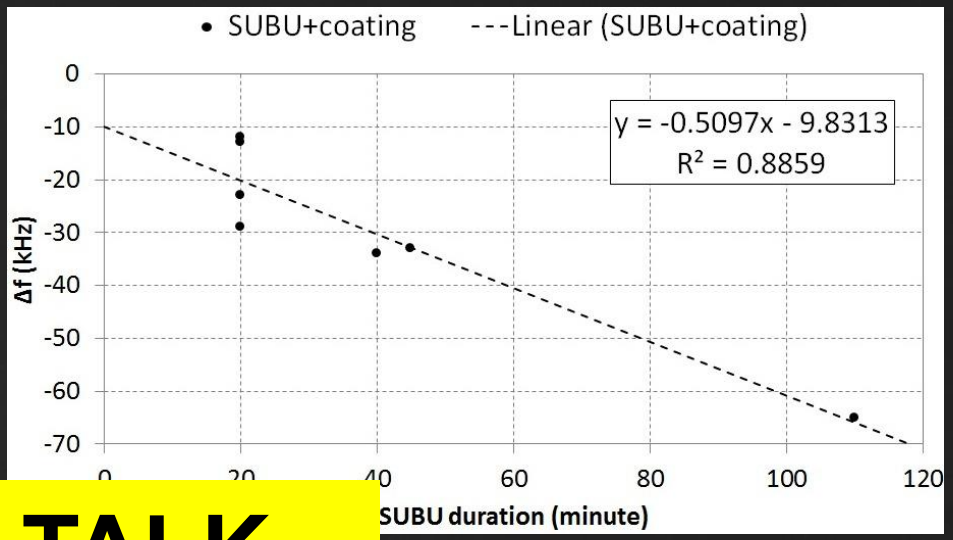
Something went wrong…

The first cavities had a higher-than-expected Δf!

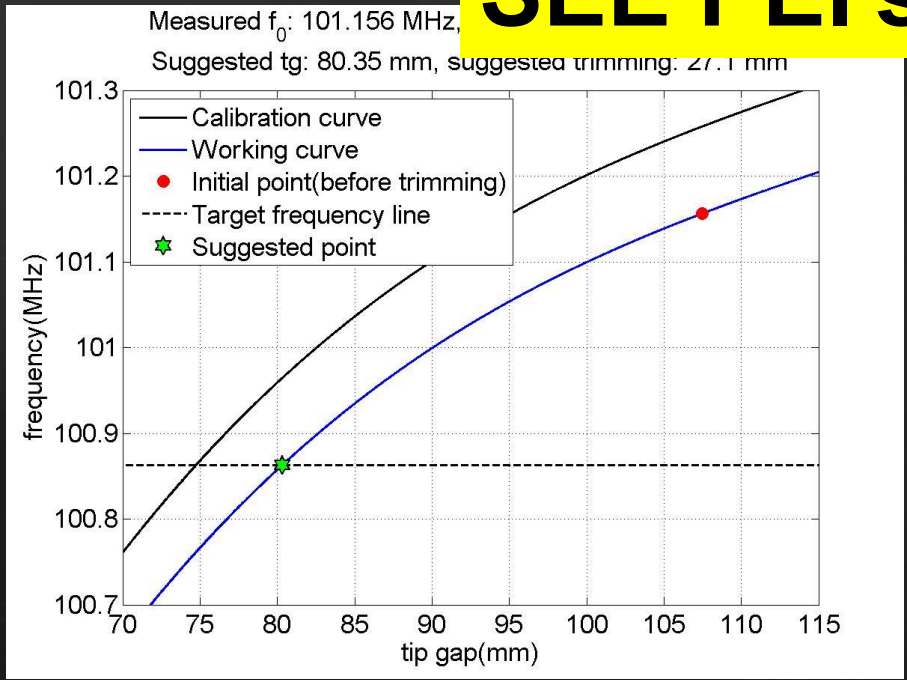
Investigations to find the reason took several months (more in Pei's talk)

Cavity tuning, mystery solved

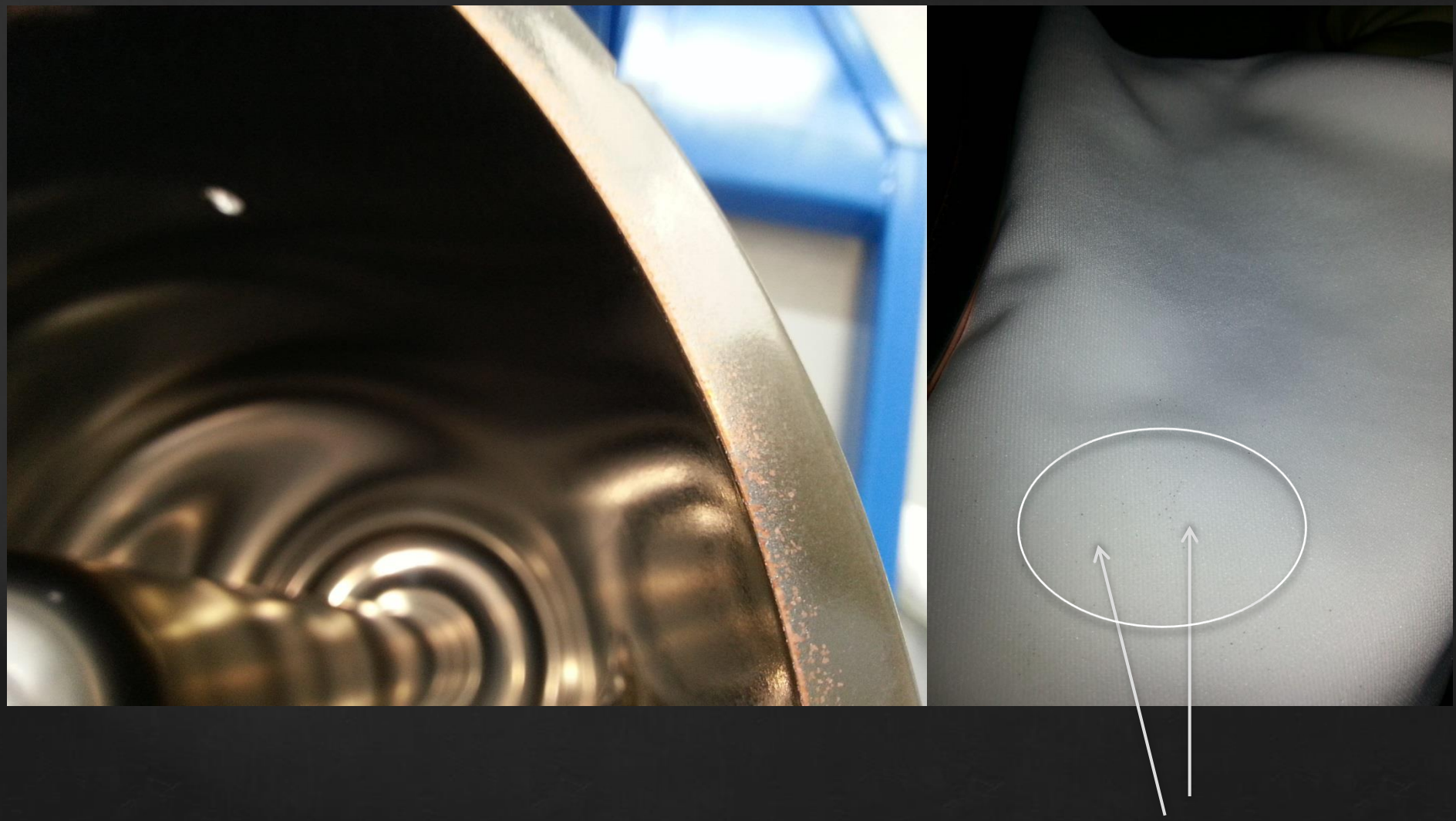
influence variables	frequency shift (kHz)
295 K to 4.5 K and air to vacuum	+371 +/- 5
chemical etching 40′	-27 +/- 3
Nb coating	



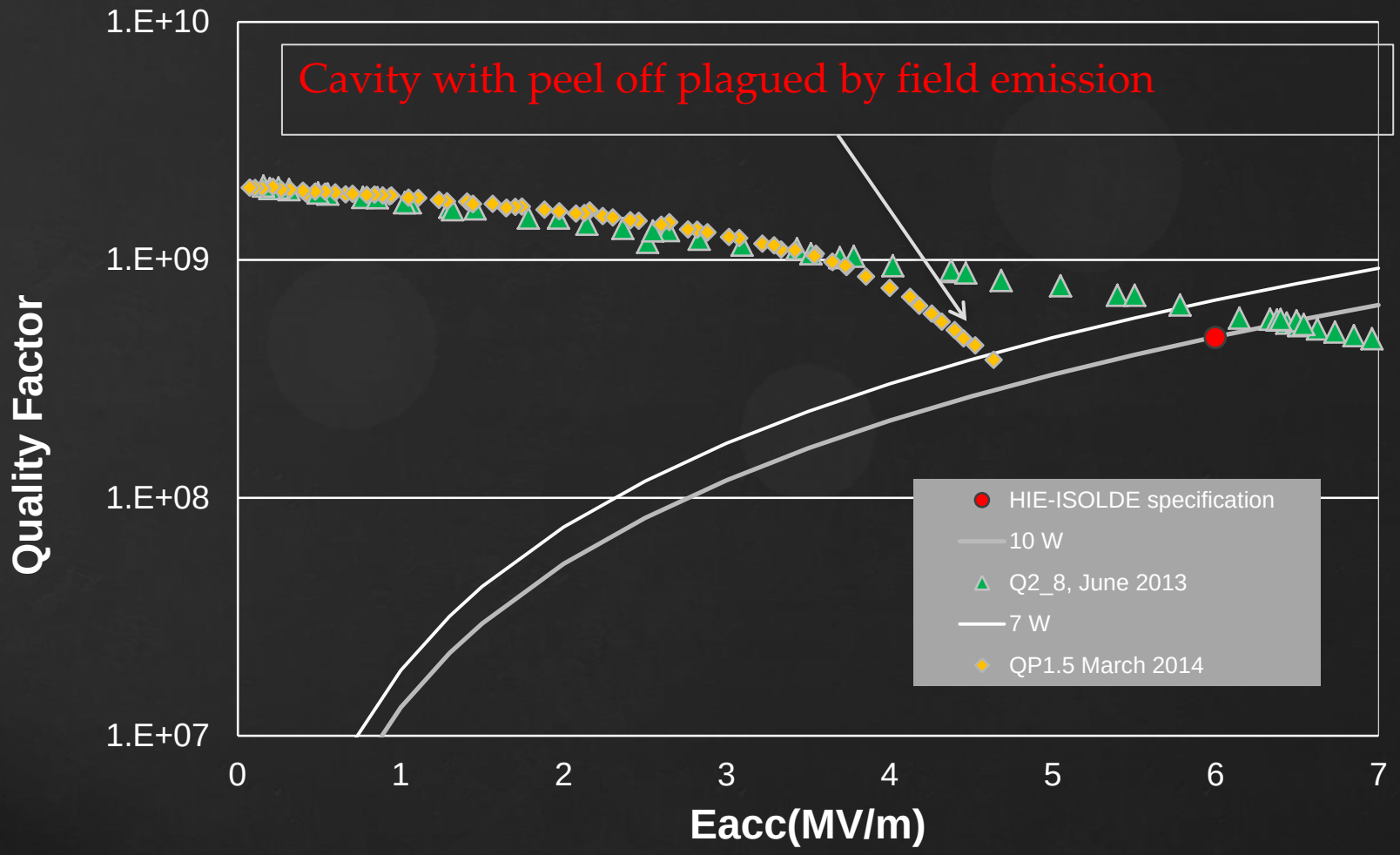
SEE PEI's TALK



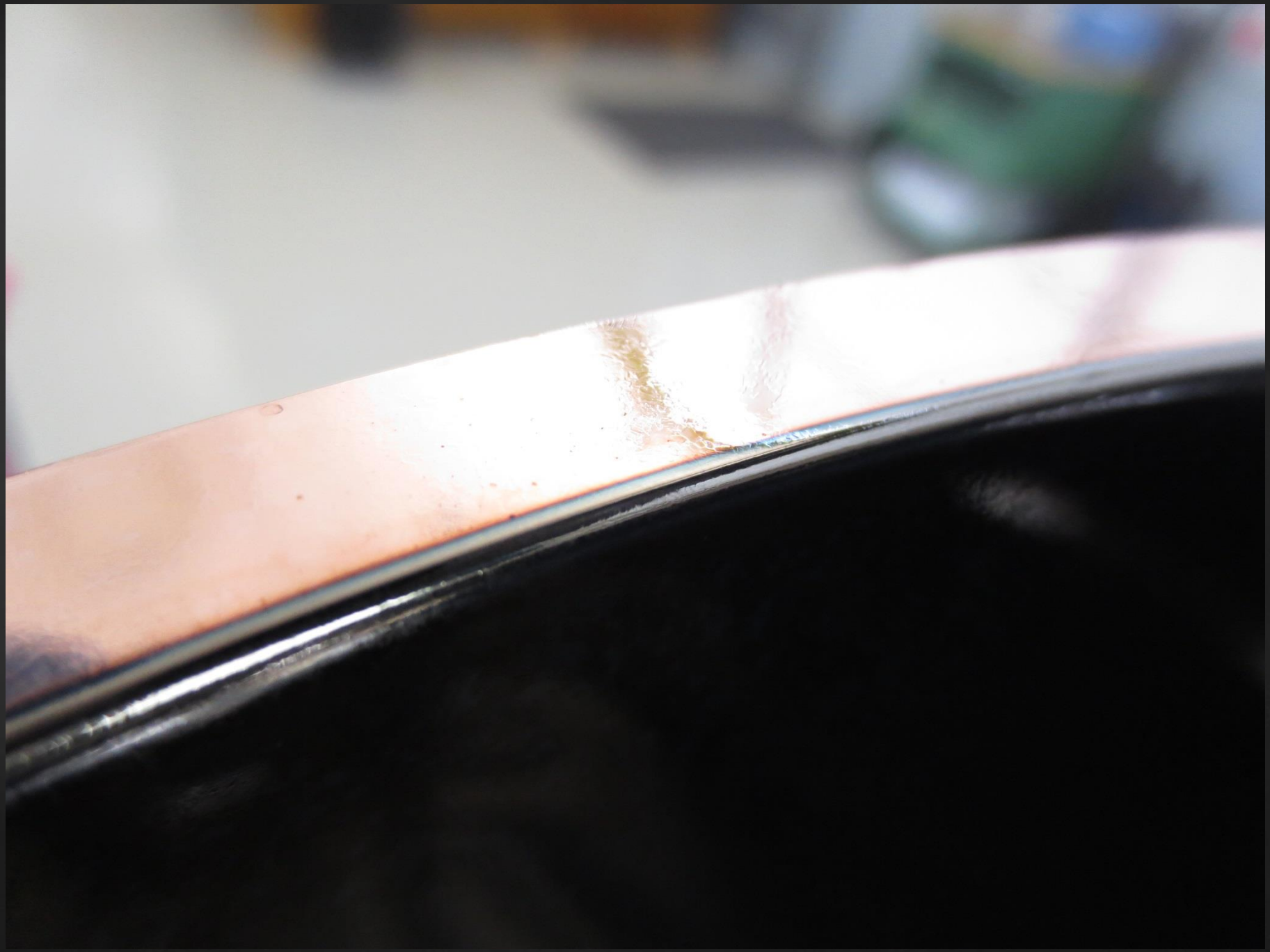
Peel off of RF contact: the problem



Peel off of RF contact: the problem



Peel off of RF contact: the solution



Cavity production workflow

Cavity tuning

Surface treatment

Rinsing cleanroom assembly

Niobium

reception

process

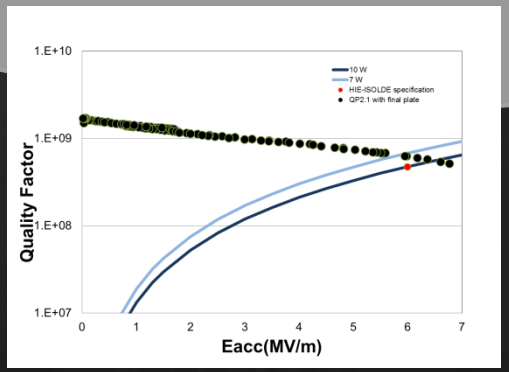
water rinsing (dust free) Cavity closure

End: Cavity storage

RF test

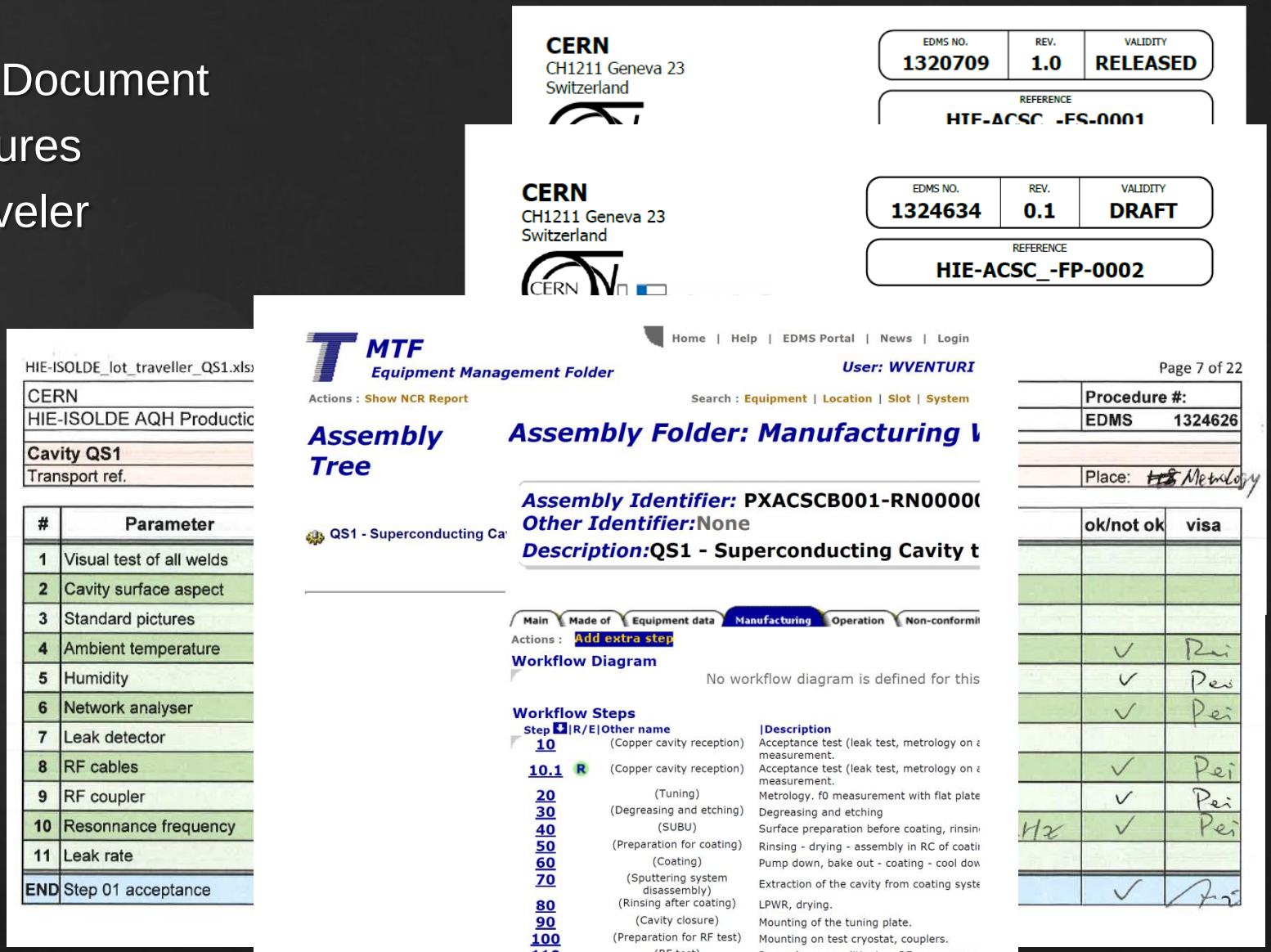
Test cryostat preparation

SEE NOEMIE's TALK



Documentation structure

- Master Document
- Procedures
- Lot Traveler
- MTF



CERN
CH1211 Geneva 23
Switzerland

EDMS NO.	REV.	VALIDITY
1320709	1.0	RELEASED

REFERENCE
HIE-ACSC_-ES-0001

CERN
CH1211 Geneva 23
Switzerland

EDMS NO.	REV.	VALIDITY
1324634	0.1	DRAFT

REFERENCE
HIE-ACSC_-FP-0002

HIE-ISOLDE_lot_traveller_QS1.xls

CERN
HIE-ISOLDE AQH Productic

Cavity QS1
Transport ref.

#	Parameter
1	Visual test of all welds
2	Cavity surface aspect
3	Standard pictures
4	Ambient temperature
5	Humidity
6	Network analyser
7	Leak detector
8	RF cables
9	RF coupler
10	Resonnance frequency
11	Leak rate
END	Step 01 acceptance

MTF
Equipment Management Folder

Home | Help | EDMS Portal | News | Login

User: WVENTURI

Actions : Show NCR Report

Search : Equipment | Location | Slot | System

Assembly Tree

QS1 - Superconducting Ca

Assembly Folder: Manufacturing V

Assembly Identifier: PXACSCB001-RN0000(
Other Identifier: None
Description: QS1 - Superconducting Cavity t

Main | Made of | Equipment data | Manufacturing | Operation | Non-conformi

Actions : Add extra step

Workflow Diagram

No workflow diagram is defined for this

Workflow Steps

Step	R/E	Other name	Description
10		(Copper cavity reception)	Acceptance test (leak test, metrology on a measurement.
10.1	R	(Copper cavity reception)	Acceptance test (leak test, metrology on a measurement.
20		(Tuning)	Metrology. f0 measurement with flat plate
30		(Degreasing and etching)	Degreasing and etching
40		(SUBU)	Surface preparation before coating, rinsin
50		(Preparation for coating)	Rinsing - drying - assembly in RC of coati
60		(Coating)	Pump down, bake out - coating - cool dow
70		(Sputtering system disassembly)	Extraction of the cavity from coating syste
80		(Rinsing after coating)	LPWR, drying.
90		(Cavity closure)	Mounting of the tuning plate.
100		(Preparation for RF test)	Mounting on test cryostat, couplers.
110		(RF test)	Pump down, conditioning, RF measureme

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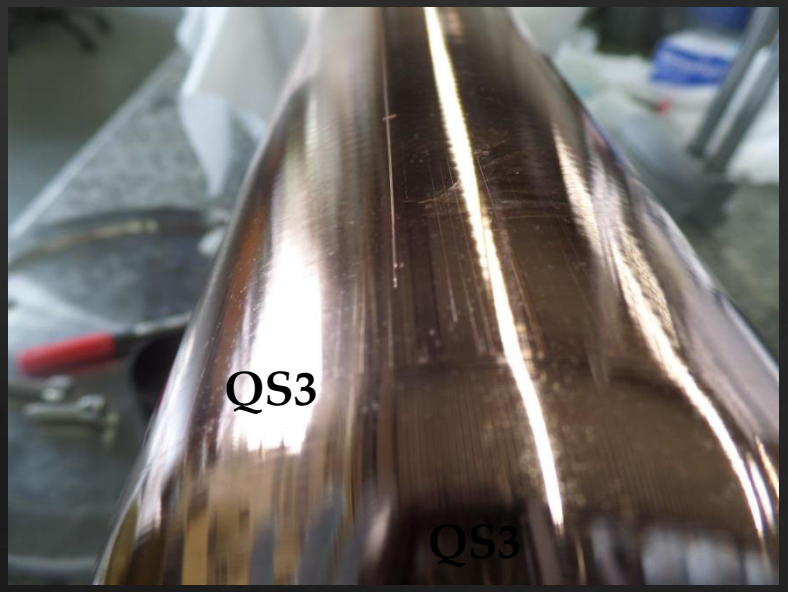
Procedure #:	
EDMS	1324626

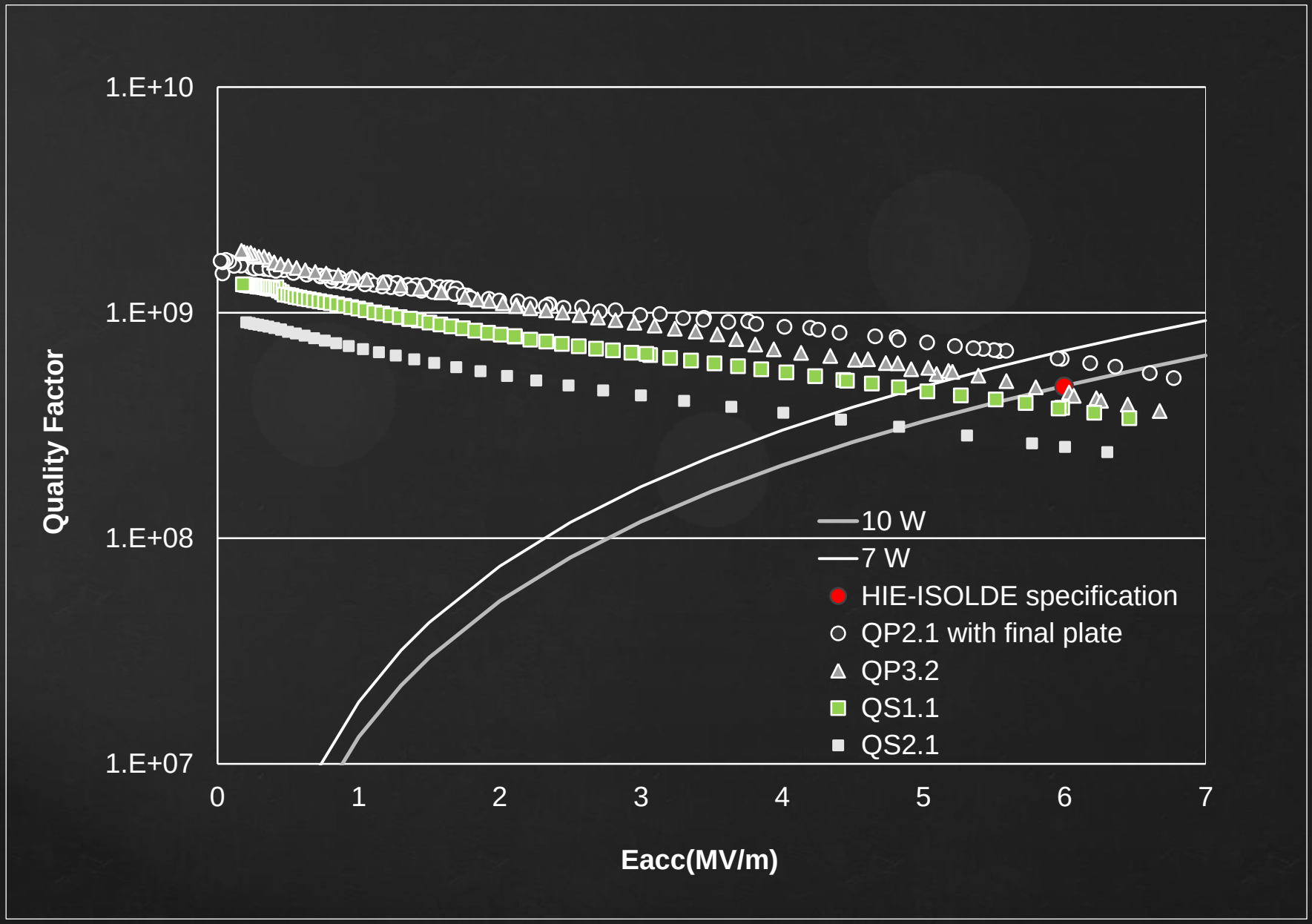
Place: ~~EBS~~ Metrology

ok/not ok	visa
✓	Rei
✓	Pei
✓	Pei
✓	Pei
✓	Pei
✓	Pei
✓	

Series substrates “teething” problems



Performance of the first 4 series cavities



RF systems (Power and LLRF)

- Low microphonics; sensitivity to He pressure
  ~ 0.01 Hz/mbar, no beam loading → high Q_L in operation
- → Eased design for the input coupler
- → 700 W solid state RF amplifiers

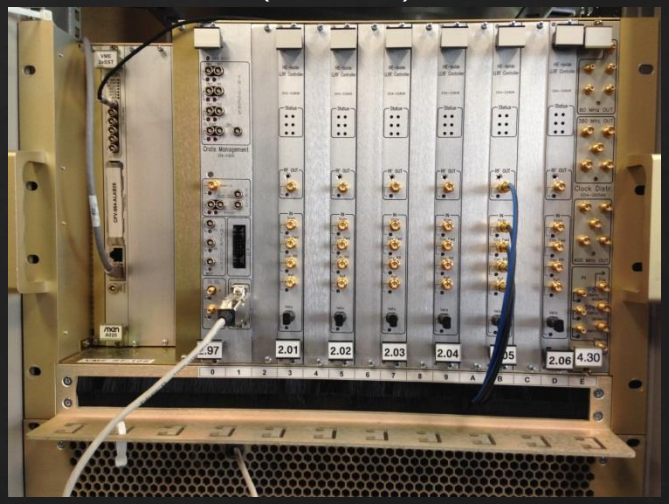
- State of the art digital LLRF system
  - Direct RF sampling
  - Digital quadrature demodulation
  - Direct RF generation by DAC
  - VME form factor, 1 LLRF controller card per cavity

- LLRF system installed in 14 shielded racks

- Reference RF phase distributed over the length of linac to allow automatic cavity phasing for different species

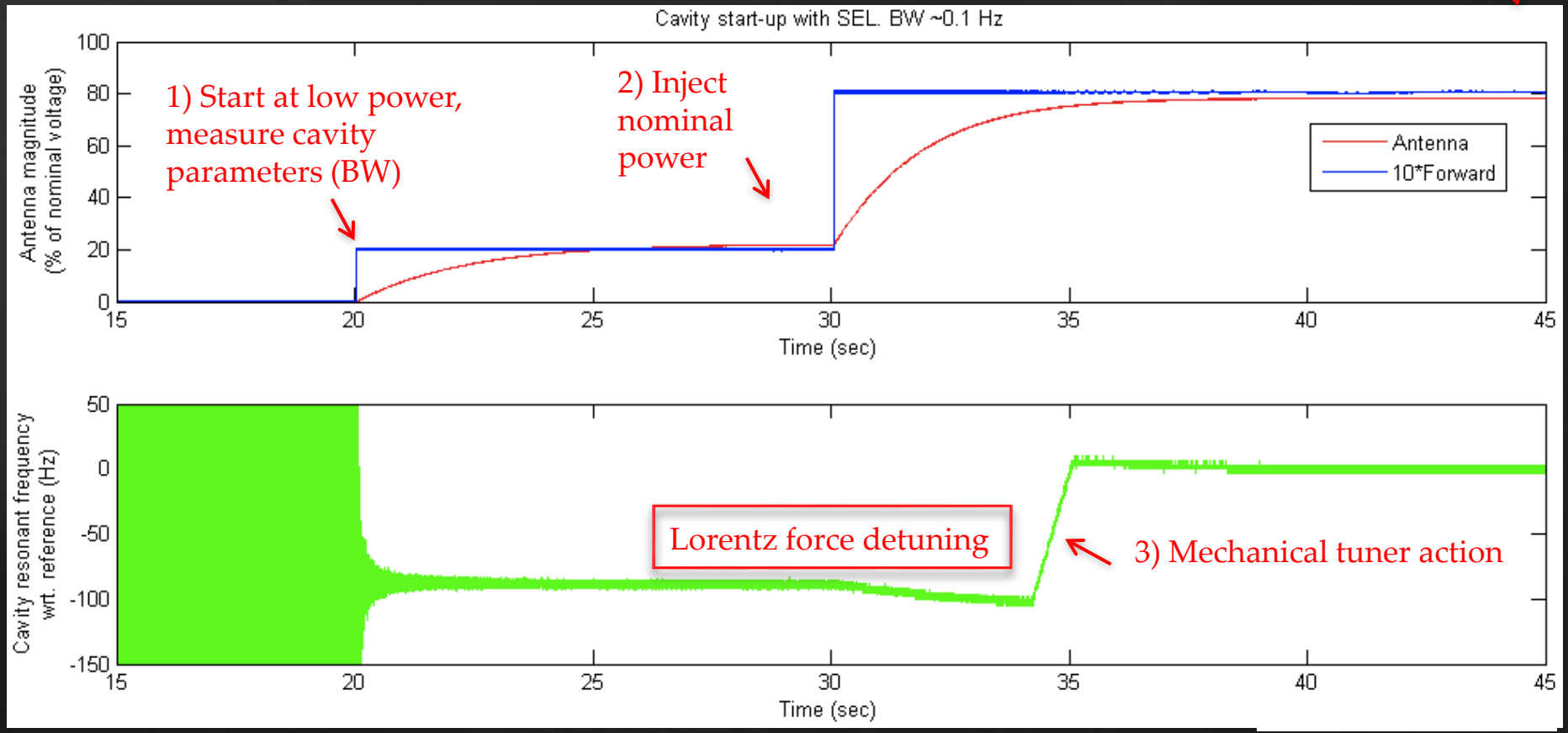
LLRF controller for one cavity

LLRF system for a complete cryomodule (6 cavities)



Low-Level RF system

- Example of a cavity start up with self excited loop



Conclusion

The HIE-ISOLDE working group on accelerating structures was the crucible of all the developments which made possible to achieve the specified performance
of the HIE ISOLDE superconducting cavities.

The CATHI fellows played a key role: thank you!

Much work and unknowns are still in front of us towards the final goal of delivery the first beams from HIE-ISOLDE to the experiments, but all the ingredients are now in our hands thanks to the work of these years

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The HIE ISOLDE International Advisory Panel

The CERN management

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