Superconducting cavity developments for the next generation of ISOL facilities (HIE ISOLDE)

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Acknowledgement

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Overview

- Technologies for superconducting quarter wave resonators
- Nb sputter cavities
- Nb-Cu sputtered QWR at LNL-INFN for the ALPI Linac
- The HIE ISOLDE project, Nb-Cu sputtered QWR at CERN
- Latest results of HIE ISOLDE cavities

Technologies for SC QWR

- **Bulk Nb with high RRR and EB welds**
  - Available from industry:
  - High gradients at low dissipated power are easier
  - Difficulties in operation (microphonics, high RF power needs)
- **Nb clad- copper**
  - External conductor in N-Cu, shaft in bulk Nb
  - High performances (sensitive to Q disease)
- **Superconducting coatings** (mechanical and thermal stability, lower cost)
  - **Electroplating of Pb on Copper**
  - Limited to few MV/m due to low B_c of lead
  - Might still be interesting for complicated shapes
  - **Nb sputtering on copper**

  Higher performance than lead plating, can compete with bulk Nb in the 100 MHz and at 4.2 K

Nb sputter technology (history)

- It all started at CERN in the early 80’s (*C. Benvenuti, N. Circelli, M. Hauer, Applied Physics Letters 45, 583 ,1984*)
- The magnetron sputtering technology was chosen for the phase 2 of LEP and industrialized
- 268 Nb/Cu elliptical cavities (352 MHz) installed in LEP
- 16 Nb/Cu elliptical cavities (400 MHz) installed in LHC
- CERN continued the research on elliptical cavities during the 1990 (see for example *C. Benvenuti, S. Calatroni, M. Hakovirta, H. Neupert, M. Prada and A.-M. Valente, Proceedings of the 10th workshop on RF Superconductivity, 2001, Tsukuba, Japan*)

Nb sputter on Cu technology

The good features

- Thermally stable (initial motivation)
- Much cheaper raw material
- Possibility to re use the same substrate, no scrap material, replace bad coatings
- Stiffness, no microphonics, can work with narrow BW if no beam loading
- Power coupler simplified, no high power RF, no active tuning and complicated feedback systems
- Less sensitive to earth magnetic field: saving on magnetic shielding
- Possibility for new SC materials

The drawback

- For high frequency, high field (2 K) applications; outperformed by bulk Nb
  - Higher residual surface resistance
  - Q slope
- Much less industrialized

More history: the Nb-Cu QWR for ALPI in INFN-LNL

- Research program was started in 1988 *(V. Palmieri, R. Preciso, V. L. Ruzinov, S. Yu. Stark, L. Badan, A. M. Porcellato , Proceedings of the 5th Workshop on RF superconductivity, 1991*)
- By 1993 reliable results were reached: three prototypes overcome 6 MV/m at 7 W
- 1995 first 4 resonators installed in ALPI (performance degradation on line)
- 1997 new series of QWR with improved design : 5.7- 7 MV/m at 7 W
- 1998 second cryostat with 4 QWR operates at 6 MV/m with beam, R/D is stopped
- 1999 **ALPI upgrading program** launched: **turn old Pb plated to Nb sputtered cavities**
- 2003 the whole medium beta section of ALPI is upgraded → +60% energy gain

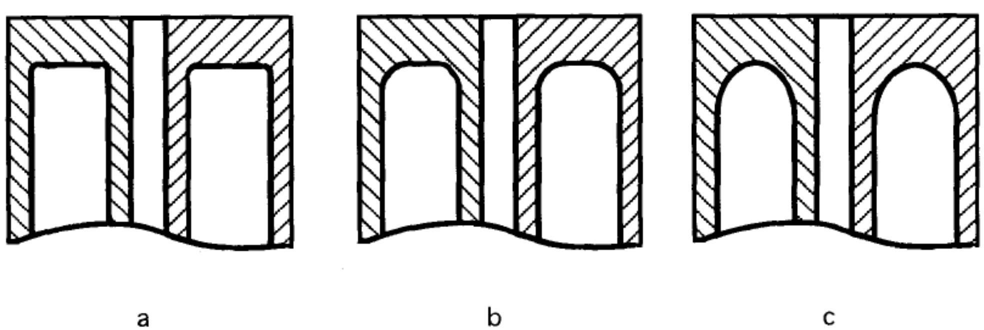
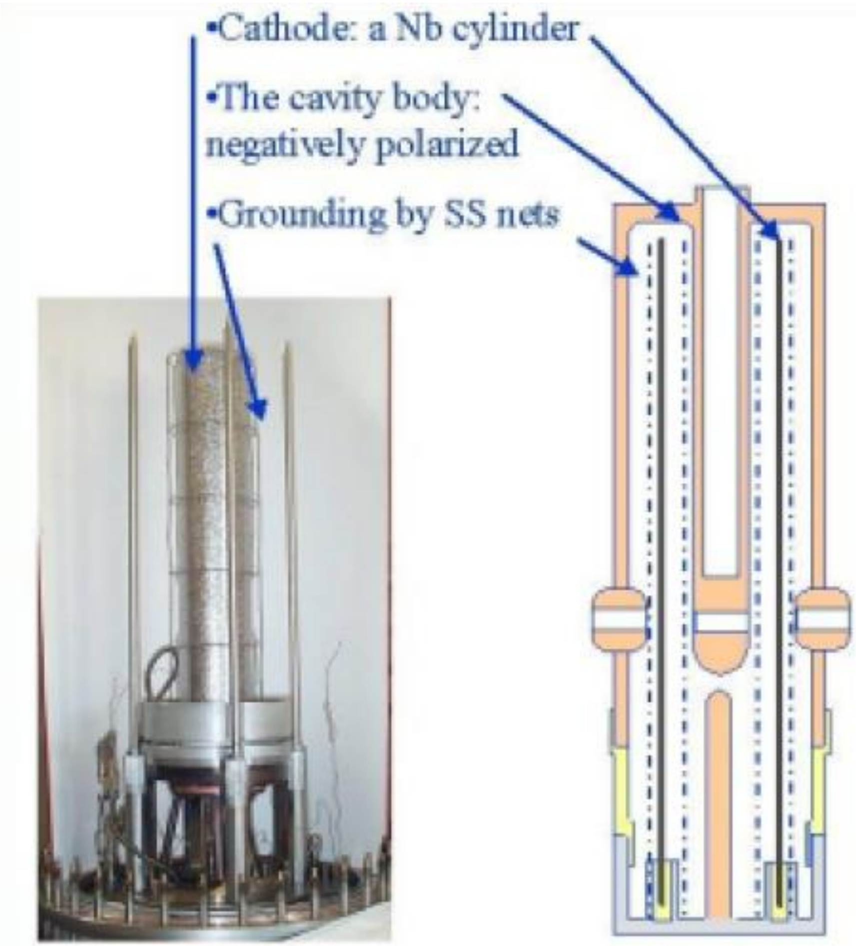


Fig. 6. Detail of resonator geometry: a) old model with curvature radius of 10 mm; b) modifyed model with curvature radius of 20 mm; c) definitive model with curvature radius of 30 mm.

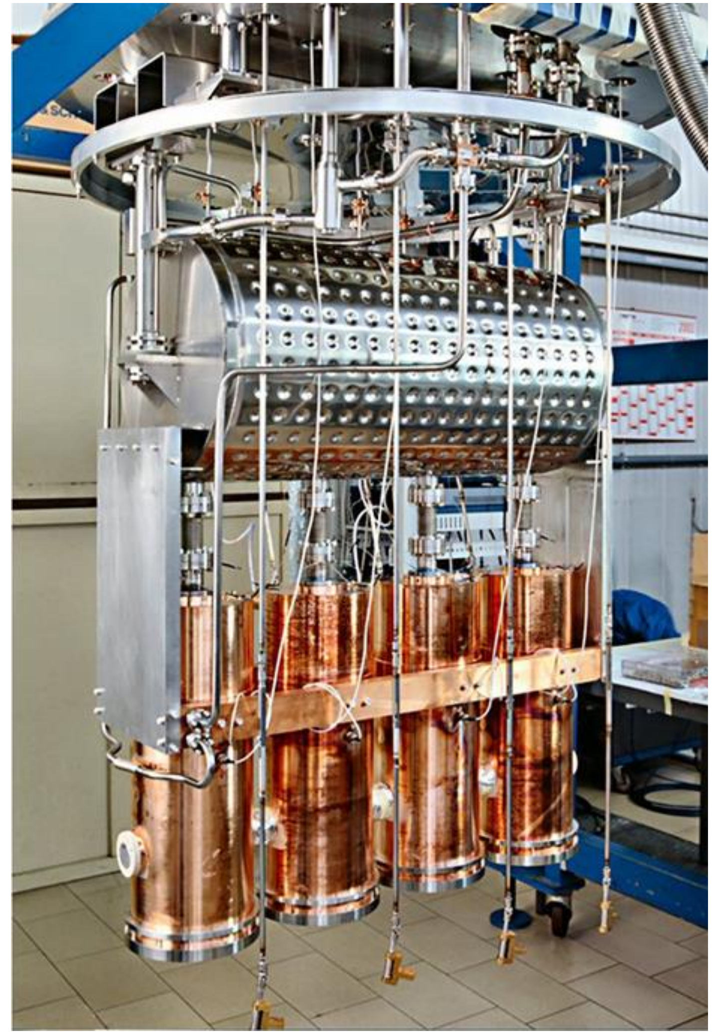
Evolution of resonator geometry (from *V. Palmieri, V. L. Ruzinov, S. Yu. Stark, L. Badan, A. M. Porcellato, R. Preciso, F. Chiurlotto, M. Morvillo; Proceedings of the 6th Workshop on RF superconductivity, 1993)*

Bias sputtering configuration



From Pramana- Journal of physics, Vol 59, No. 5, November 2002, pp. 871-880

ALPI cryostat



From www.lnl.infn.it

HIE ISOLDE cavities

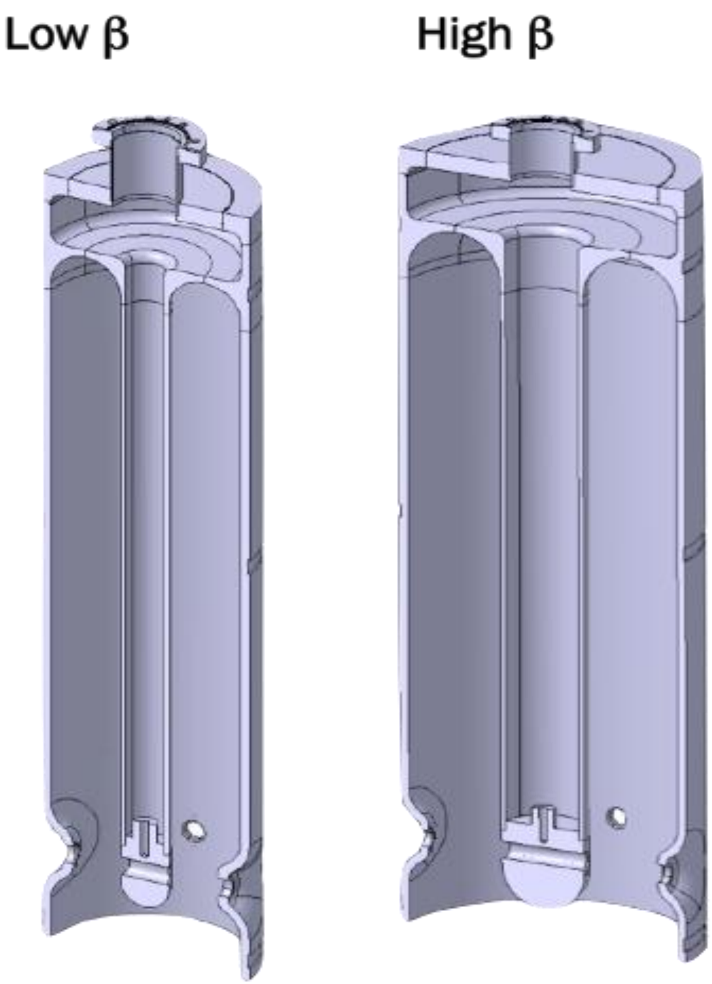
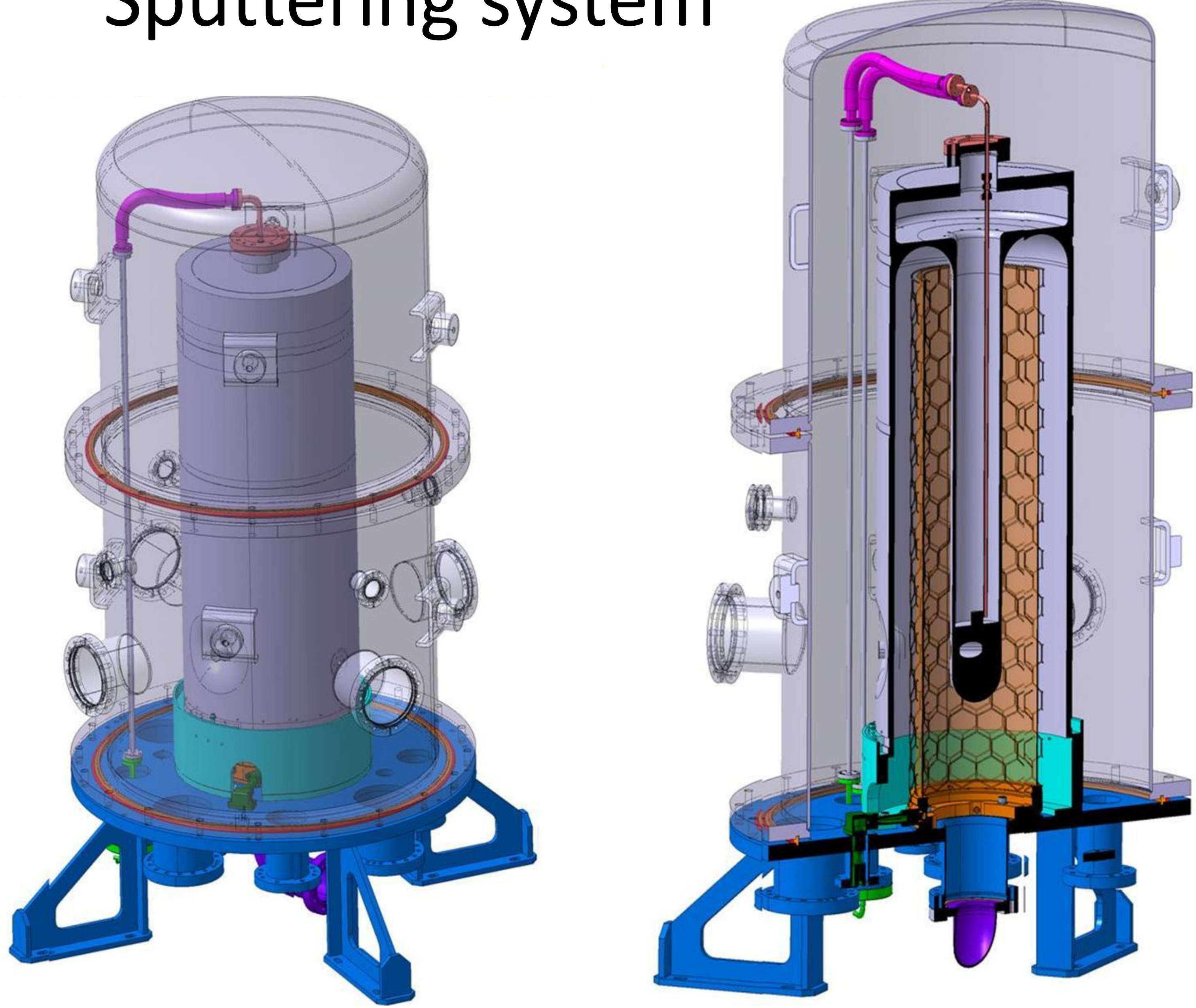


Table 1: Cavity design parameters

Cavity	**Low β**	**highβ**
No. of Cells	2	2
f (MHz)	101.28	101.28
β_0 (%)	6.3	10.3
Design gradient E_{acc}(MV/m)	6	6
Active length (mm)	195	300
Inner conductor diameter (mm)	50	90
Mechanical length (mm)	215	320
Gap length (mm)	50	85
Beam aperture diameter (mm)	20	20
$U/E_{acc}{}^2$ (mJ/(MV/m)^2	73	207
E_{pk}/E_{acc}	5.4	5.6
H_{pk}/E_{acc} (Oe/MV/m)	80	100.7
R_{sh}/Q (Ω)	564	548
$\Gamma = R_s \cdot Q_0$ (Ω)	23	30.6
Q_0 for 6MV/m at 7W	$3.2 \cdot 10^8$	$5 \cdot 10^8$
TTF max	0.85	0.9
No. of cavities	12	20

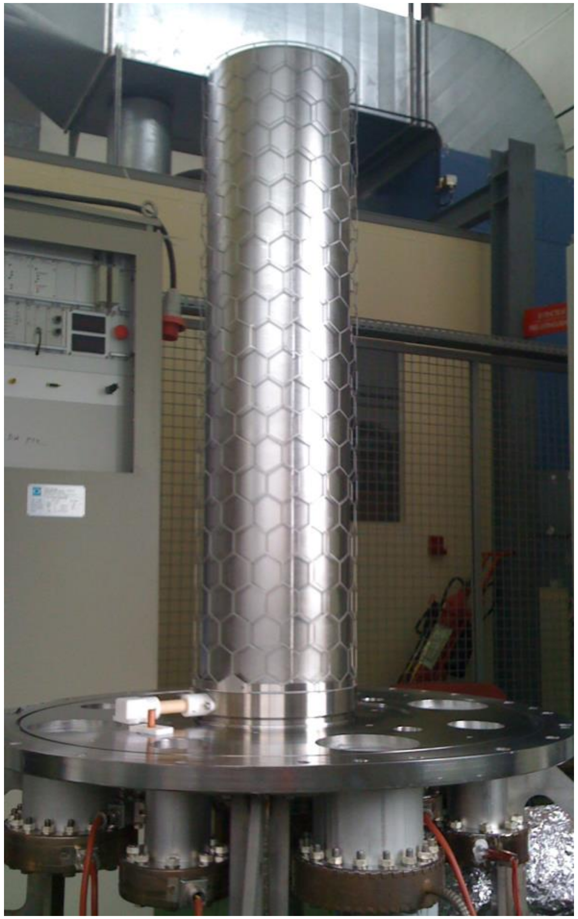
A. D'Elia, R. M. Johnes, M. Pasini, Proceedings of SRF2009, Berlin, Germany

Sputtering system

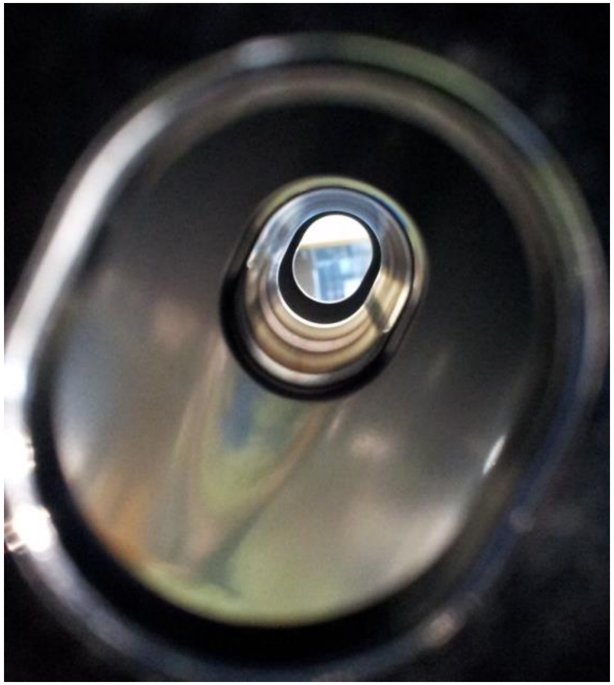


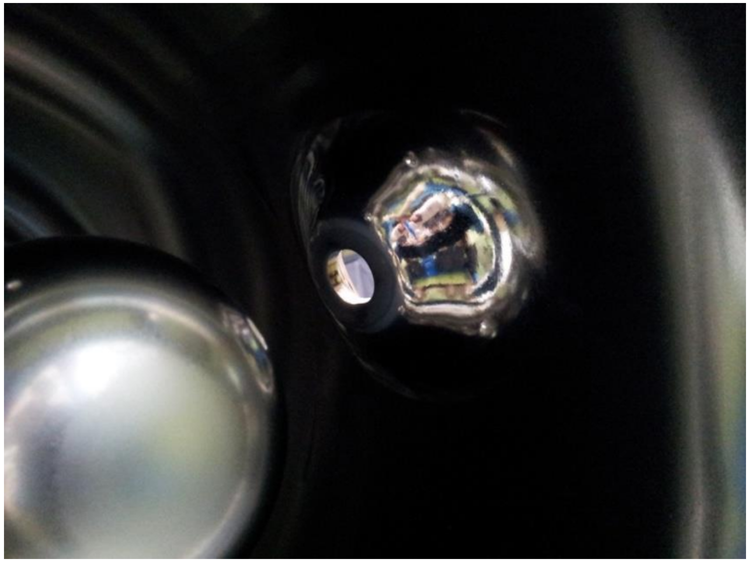
G. Lanza, S. Calatroni, L. Marques Antunes Ferreira, A. Gustafsson, M. Pasini, P. Trilhe, Vincenzo Palmieri; Proceedings of SRF2009, Berlin, Germany

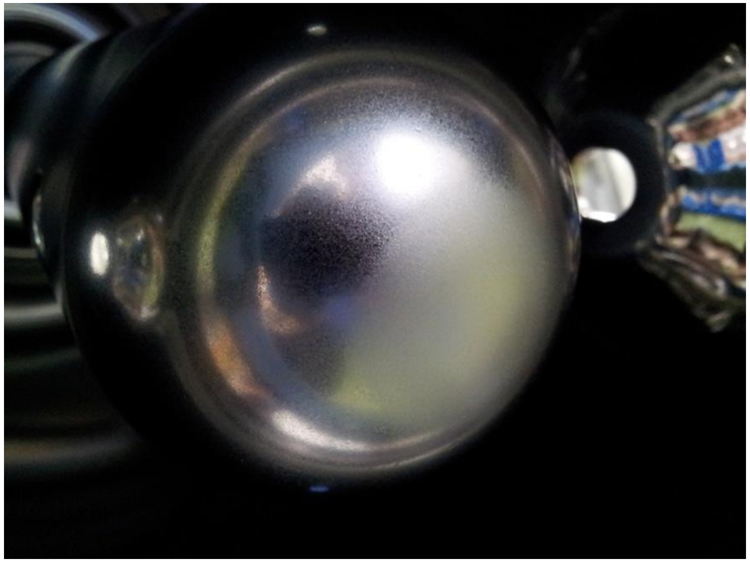
CERN Sputtering system for QWR



Nb sputtered cavity







RF tests in vertical cryostats

In 2012, 10 test cavities (with parameters progressively closer to the ALPI sputtering protocol), qualified at 4.5 K

New version of fundamental power coupler qualified

Dedicated experiments done to assess the contribution of the bottom plate contact to the total loss

Dedicated experiment done to assess the sensitivity of the cavity Q to stray magnetic field from the superconducting solenoid

Dedicated experiment done to check the possibility that Q switches originated in the transition of the bottom plate to the normal conducting state

Improvements to the test setup
(infra red lamps, mobile coupler, spare inserts, logistics)

→ Turnaround of 2 weeks demonstrated

Q2_5: November 2011

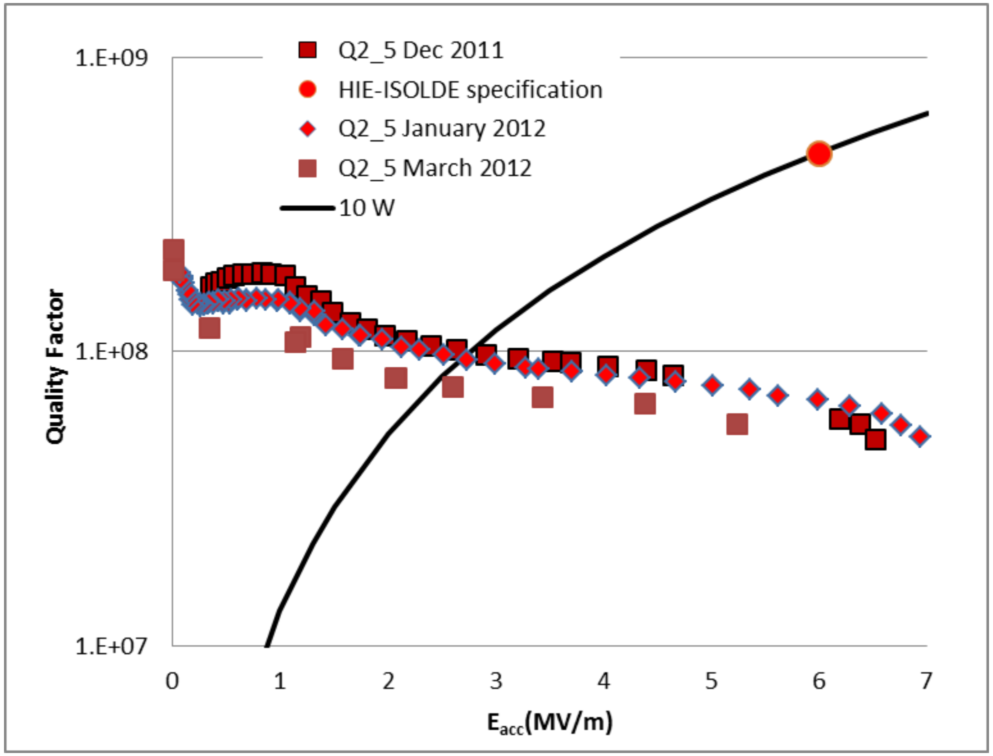
first cavity with bias diode method and increased coating temperature

Parameter/feature	HIE ISOLDE cavity CERN	ALPI cavity INFN-LNL
Substrate treatment	SUBU	Tumbling, EP then SUBU
Rinsing water pressure	5-6 bar	100 bar
Bake out temperature	120 ° C (<sputtering T)	600 ° C (>sputtering T)
Sputtering temperature	100 ° C → **485°C**	300 → 500 °C
Sputtering pressure	1.4 10^{-1} mbar	2 10^{-1} mbar
Number of layers	1	12-20 layers
Power	1.8 kW	5 kW (for 2.5 times smaller surface)
Cathode voltage	850 V	1 kV
Bias voltage	-80 V	-120 V
Total electrical energy	28 kWh	15 kWh
Auxiliary electrode	2 cm diameter, grounded	4 cm diameter (2/3 of inner conductor), rounded, bias potential
Film minimum thickness	1 µm (?)	2 µm
Sputtering gas	Krypton	Argon
Venting gas	Dry air	N_2
vacuum joint	Viton	CF

For the first time E_{acc} of 6 MV/m was reached

Q still too low, an order of magnitude

Possible ohmic source (bottom plate?)
Measurement with In gasket excluded major effect

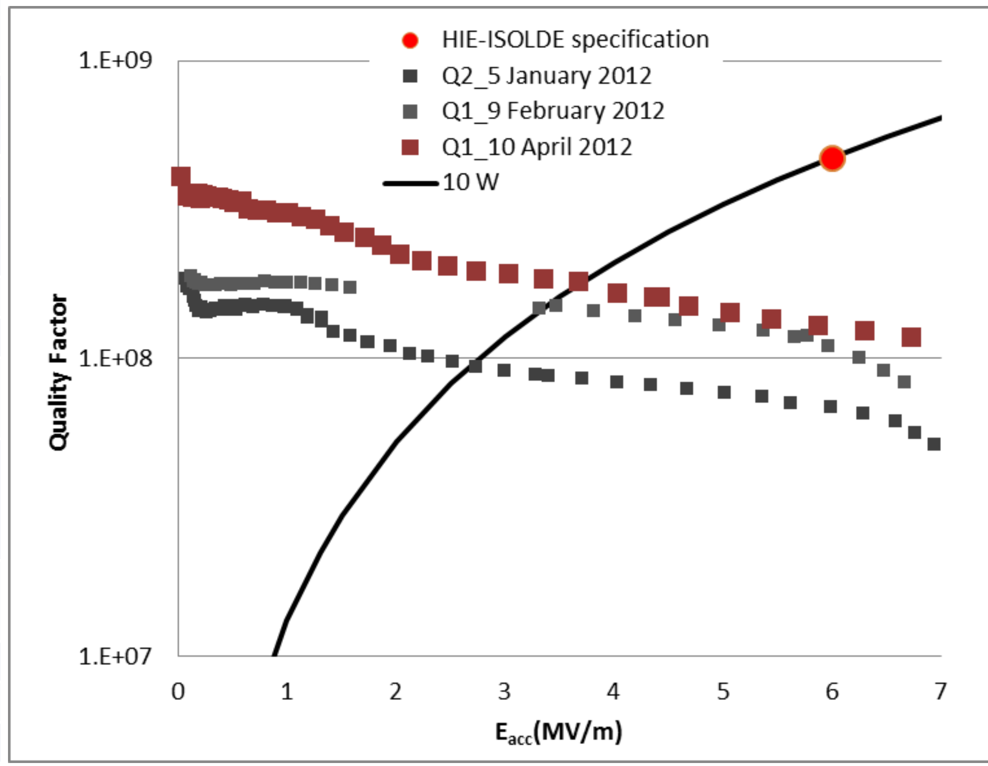


Q1_10: March 2012

SS support (reduced temperature gradient during coating); helicoflex gasket (improved vacuum)

Parameter/feature	HIE ISOLDE cavity CERN	ALPI cavity INFN-LNL
Substrate treatment	SUBU	Tumbling, EP then SUBU
Rinsing water pressure	5-6 bar	100 bar
Bake out temperature	120 ° C (<sputtering T)	600 ° C (>sputtering T)
Sputtering temperature	115°C → **590°C (gradient reduced)**	300 → 500 °C
Sputtering pressure	$2.2\ 10^{-1}$ mbar	$2\ 10^{-1}$ mbar
Number of layers	1	12-20 layers
Power	**3.6 kW→5 kW**	5 kW (for 2.5 times smaller surface)
Cathode voltage	920 V	1 kV
Bias voltage	-80 V	-120 V
Total electrical energy	32 kWh	15 kWh
Auxiliary electrode	2 cm diameter, grounded	4 cm diameter (2/3 of inner conductor), rounded, bias potential
Film minimum thickness	1 μm (?)	2 μm
Sputtering gas	Krypton	Argon
Venting gas	Dry air	N_2
vacuum joint	**Helicoflex**	CF

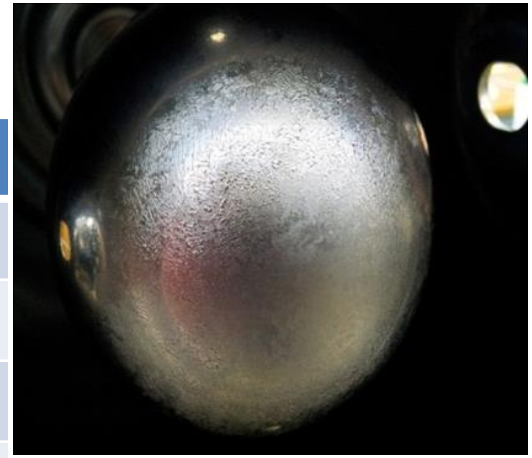
The positive trend on Q_0 with increasing dN/dt and T continued, but Q slope also increased: no much gain at 6 MV/m



Q1_11: July 2012

Several changes done to approach the ALPI parameters: IR heaters with copper screens, temperatures, power, sputtering gas, venting gas

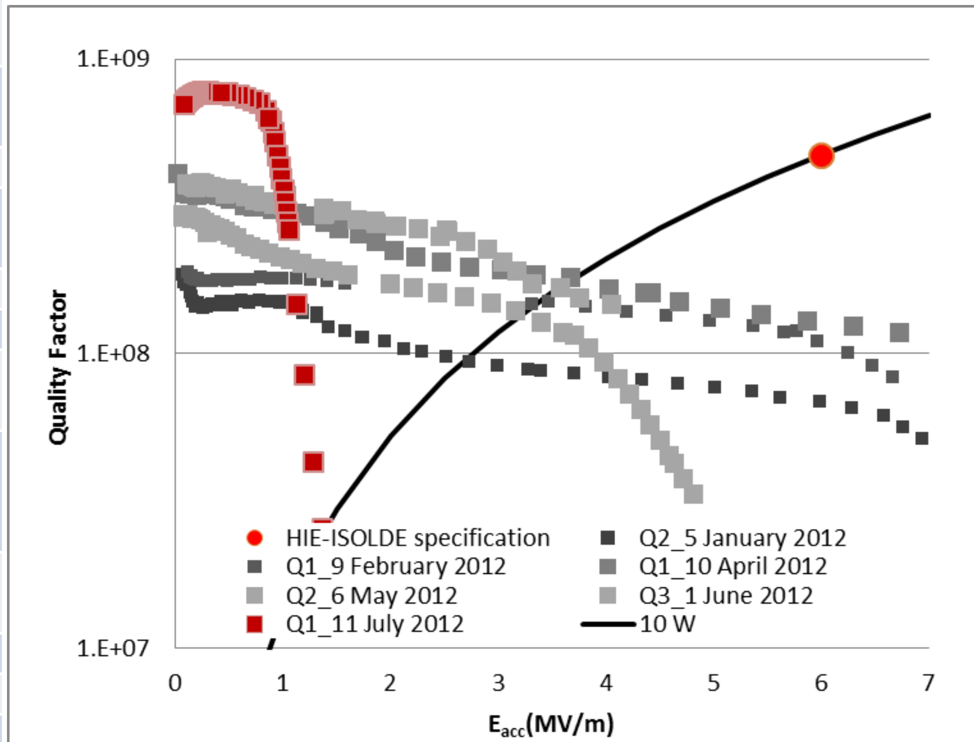
Parameter/feature	HIE ISOLDE cavity CERN	ALPI cavity INFN-LNL
Substrate treatment	SUBU	Tumbling, EP then SUBU
Rinsing water pressure	5-6 bar	100 bar
Bake out temperature	**570 °C (>sputtering T)**	600 ° C (>sputtering T)
Sputtering temperature	**300°C →400-440°C**	300 → 500 °C
Sputtering pressure	2.5 10^{-1} mbar	2 10^{-1} mbar
Number of layers	**12**	12-20 layers
Power	**2 kW→8 kW**	5 kW (for 2.5 times smaller surface)
Cathode voltage	1 kV	1 kV
Bias voltage	-80 V	-120 V
Total electrical energy	36.4 kWh	15 kWh
Auxiliary electrode	2 cm diameter, grounded	4 cm diameter (2/3 of inner conductor), rounded, bias potential
Film minimum thickness	1 µm (?)	2 µm
Sputtering gas	**Argon**	Argon
Venting gas	**N_2**	N_2
vacuum joint	**Viton**	CF



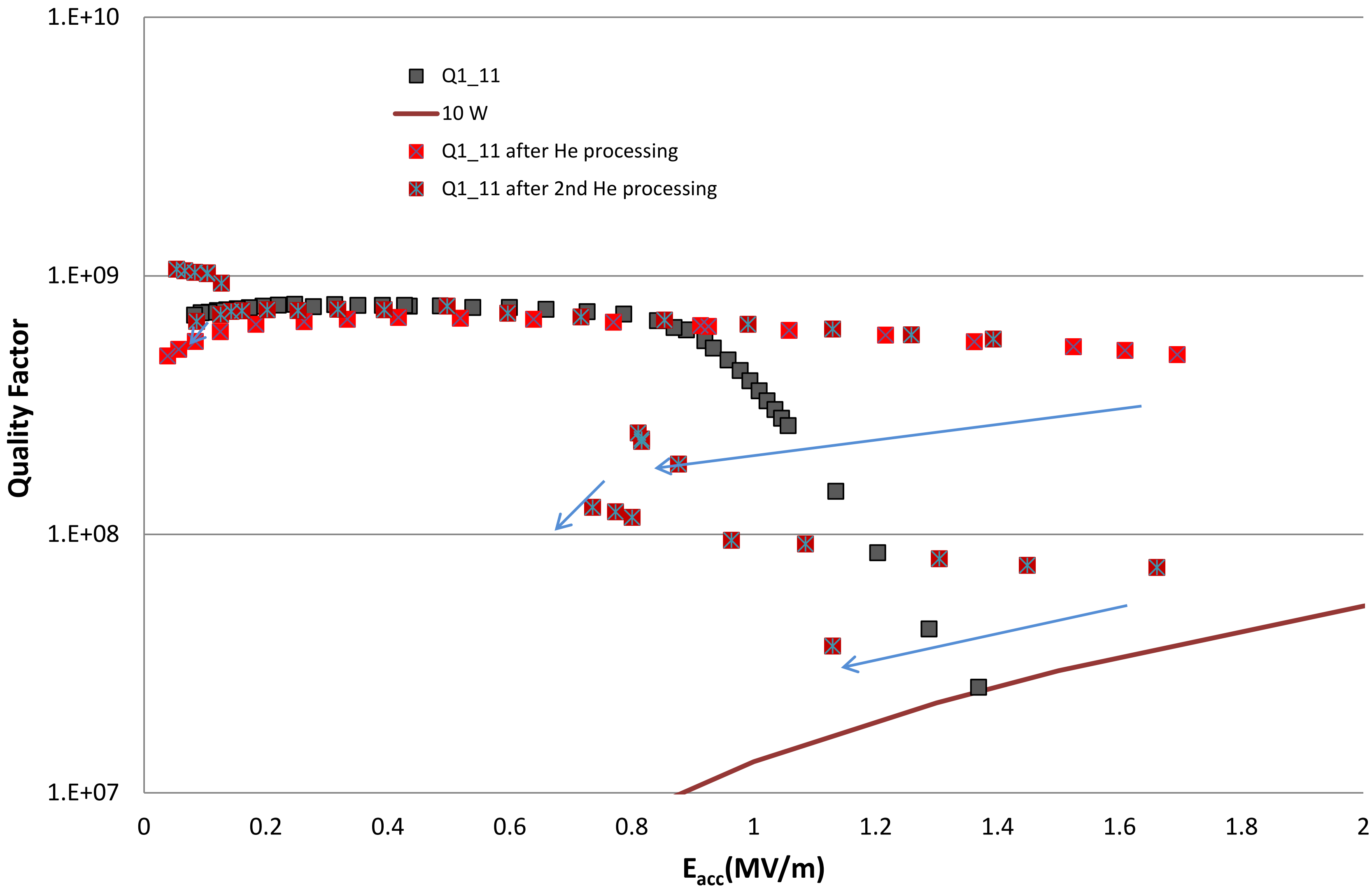
"Quantum jump" in Q_0

Bad film quality on the tip of the inner conductor

Field emission at very low field



Q switches



1.E+10
1.E+09
1.E+08
1.E+07
Quality Factor
Q1_11
10 W
Q1_11 after He processing
Q1_11 after 2nd He processing
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
E_{acc}(MV/m)

Q2_7: October 2012

Increasing film thickness by 25%

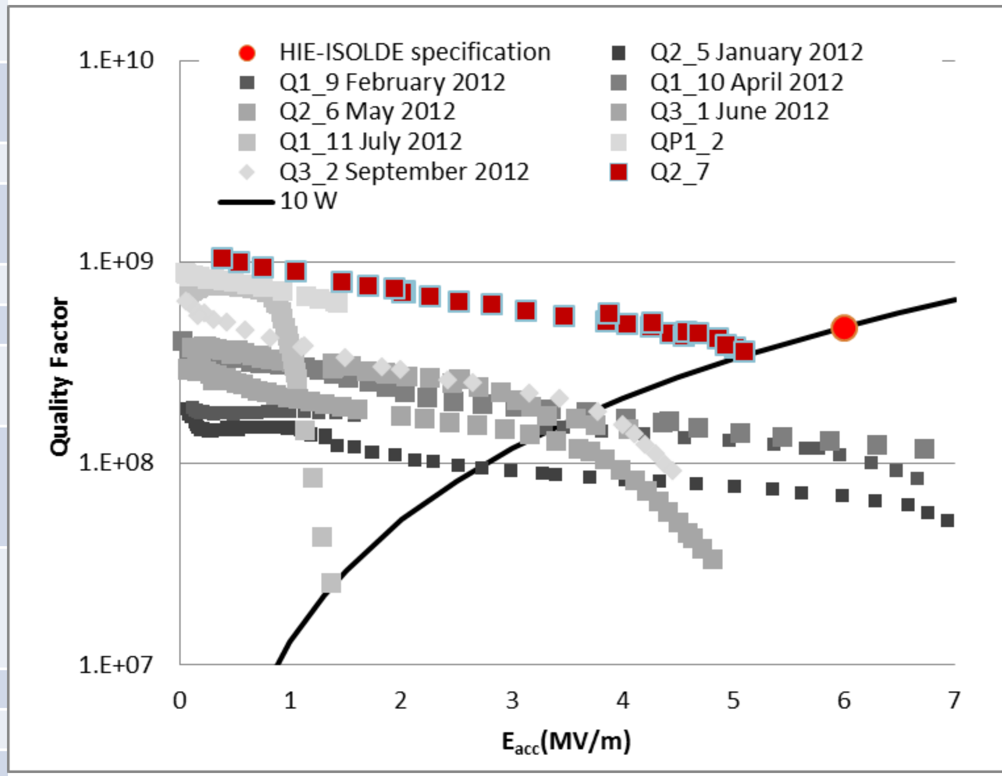
with same parameters as Q1_11

Parameter/feature	HIE ISOLDE cavity CERN	ALPI cavity INFN-LNL
Substrate treatment	SUBU	Tumbling, EP then SUBU
Rinsing water pressure	5-6 bar	100 bar
Bake out temperature	**580°C (>sputtering T)**	600°C (>sputtering T)
Sputtering temperature	**310°C →580°C**	300 → 500 °C
Sputtering pressure	2.6 10^{-1} mbar	2 10^{-1} mbar
Number of layers	**14**	12-20 layers
Power	**2 kW→8 kW**	5 kW (for 2.5 times smaller surface)
Cathode voltage	1 kV	1 kV
Bias voltage	-80 V	-120 V
Total electrical energy	**46 kWh**	15 kWh
Auxiliary electrode	2 cm diameter, **bias potential**	4 cm diameter (2/3 of inner conductor), rounded, bias potential
Film minimum thickness	Q1_11 + 25% should be1.25 but **Measured: 0.7 µm!**	2 µm
Sputtering gas	**Argon**	Argon
Venting gas	**N_2**	N_2
vacuum joint	**Viton**	CF

Reached 5 MV/m at 10 W (5.3 MeV/a for A/q of 4.5!*)

No Q switches!

Then degraded and became limited by field emission



*With 10 cavities in Phase 1

2013 developments

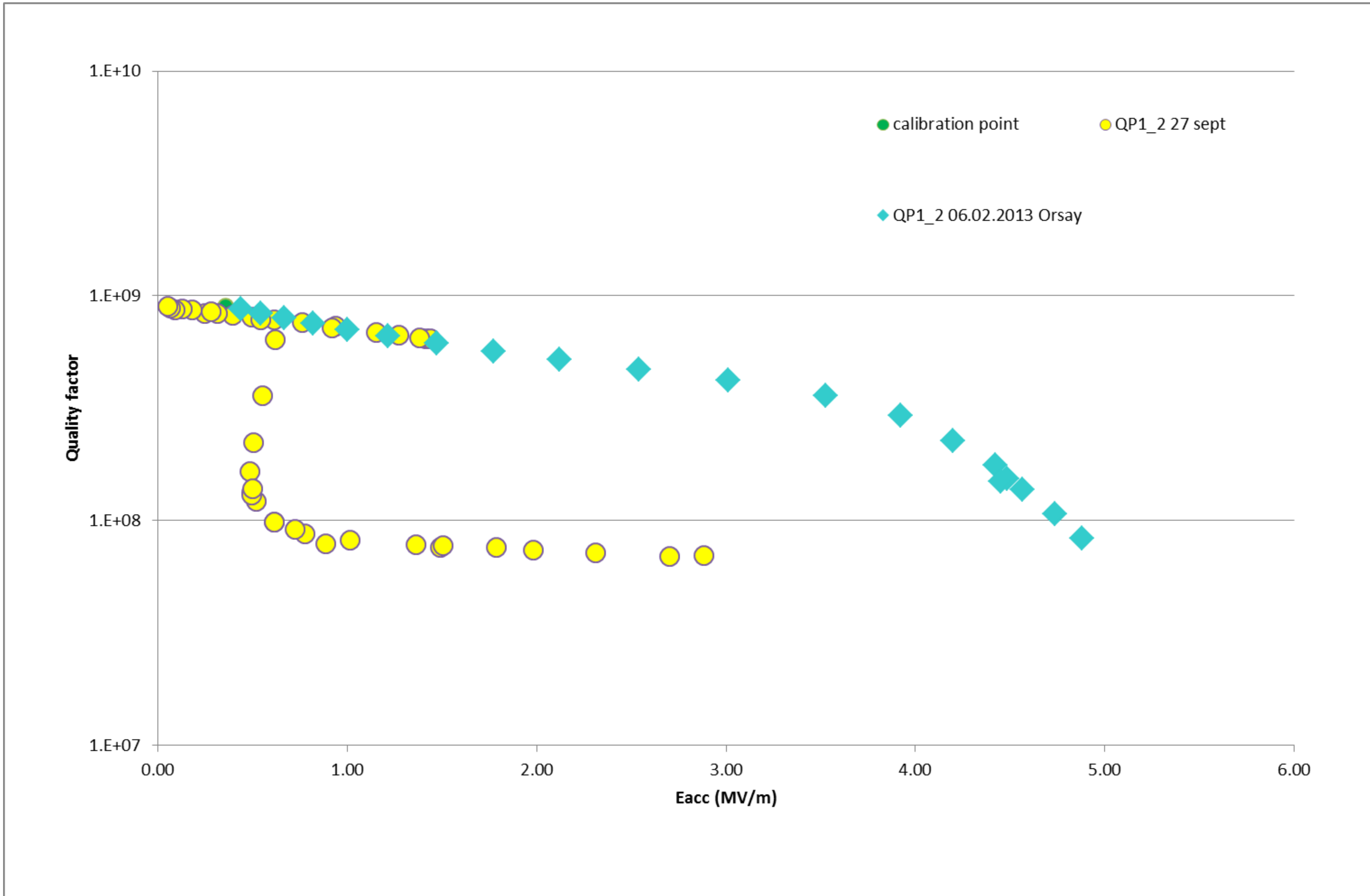
- At the end of 2012 the **main remaining issues** were clearly identified
  - **Coating rate (thickness) on cavity top was too low**
  - **Poor surface quality on tip of inner conductor** (peak E field region)
  - Q switches

- Test in Orsay of a cavity affected by Q switch confirmed results at low field, but without Q switch
- Q switch proved to be an **extrinsic effect** likely due to tuning plate

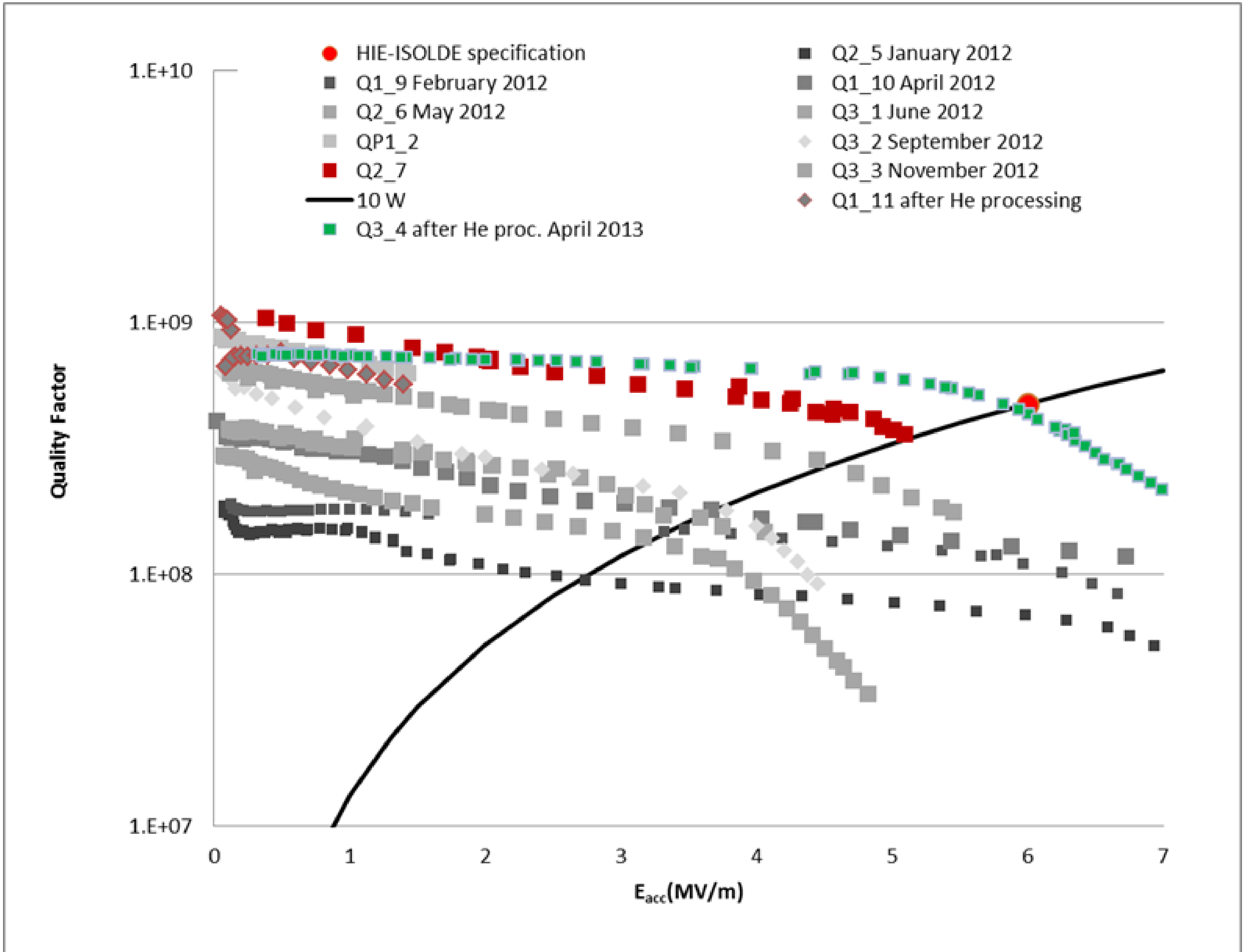
- **The cathode distance to the cavity top was decreased by 20 mm on a real cavity (Q3.4)** The same configuration was reproduced on a sample run (Q4.3)
- → **Coating rate increased by a factor two on the cavity top**

The Q3.4 cavity reached 6 MV/m at 10 W dissipated power, the HIE ISOLDE Specification

First test in Orsay (February 2013)



Second test in Orsay (April 2013)



Summary

- The Nb sputter on Cu technology for SC cavities, invented at CERN and used for LEP and LHC, is particularly interesting for RIB facilities
- INFN-LNL developed it for QWRs and used it to upgrade the ALPI heavy ion linac
- The same technology was chosen for HIE ISOLDE
- Development phase started at CERN in 2008, end 2012 cavity performance reached satisfactory levels
- Recently HIE ISOLDE specs were achieved on a prototype cavity