18th International Conference on RF Superconductivity

Review of heat treatments for low beta cavities : what's so different from elliptical cavities

D. Longuevergne

SRF2017 – July 2017 - Lanzhou

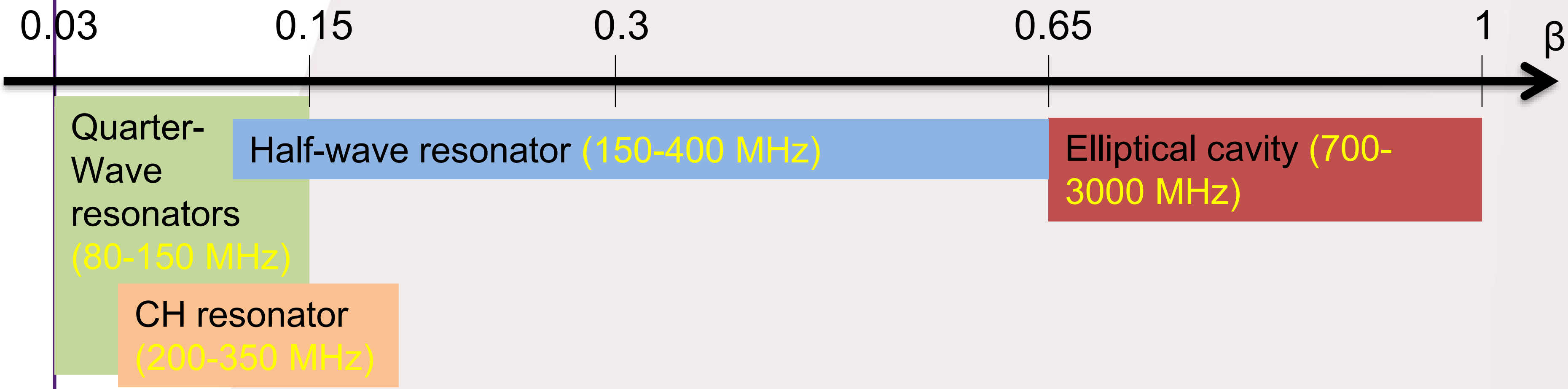
UNIVERSITÉ PARIS SUD
université PARIS-SACLAY
CNRS IN2P3 Les deux infinis
IPN INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

OUTLINE

SPECIAL THANKS TO :
- Z. Conway, ANL
- W. Yue, IMP
- E. Cenni, CEA
- Z. Yao, TRIUMF
- R. Laxdal, TRIUMF

- Introduction
- Heat treatments
  - Hydrogen degassing
  - Low temperature baking
  - Perspectives on nitrogen doping… is there one ?
- Conclusion

ACCELERATING STRUCTURES



ACCELERATING STRUCTURES

0.03 | 0.15 | 0.3 | 0.65 | 1 | β

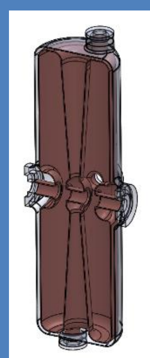
Quarter-Wave

Half-wave resonator (150-400 MHz)

Elliptical cavity (700-3000 MHz)

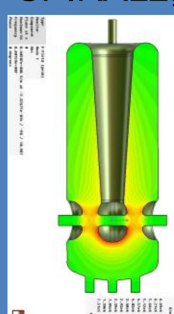
4K

IAP β=0.07, 215MHz



RISP β=0.12, 162.5MHz

SPIRAL2, β=0.12, 88 MHz



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2K

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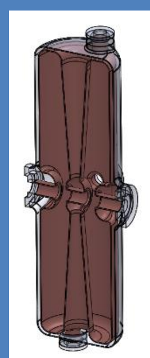

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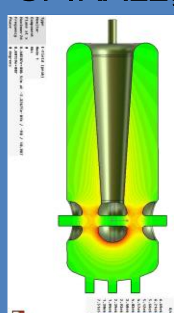
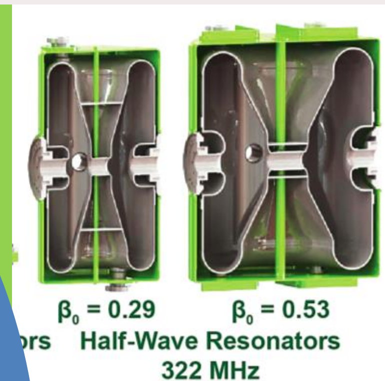
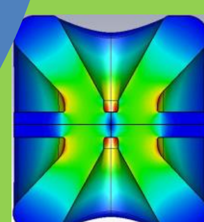


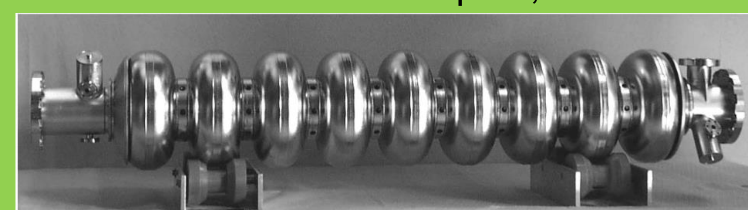


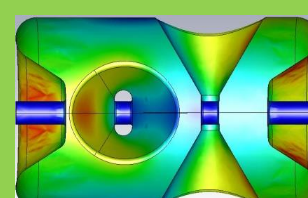


MYRRHA β=0.37, 352 MHz

ESS β=0.67, 700 MHz

XFEL β= 1, 1.3 GHz





ESS β=0.5, 352 MHz

ACCELERATING STRUCTURES

0.03 | 0.15 | 0.3 | 0.65 | 1 | β

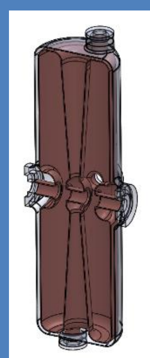
Quarter-Wave

Half-wave resonator (150-400 MHz)

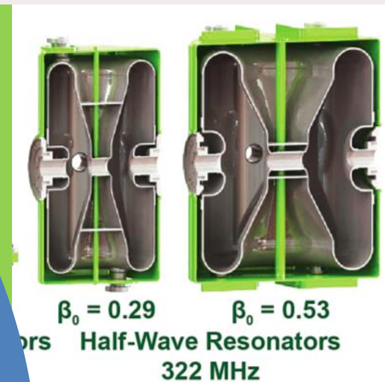
Elliptical cavity (700-3000 MHz)

4K

IAP β=0.07, 215MHz



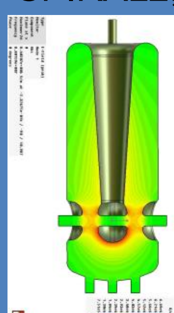
RISP β=0.12, 162.5MHz



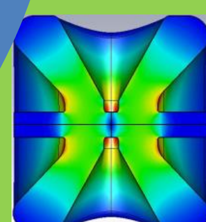
2K

ESS β=0.67, 700 MHz

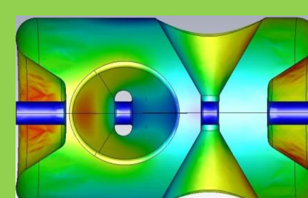
SPIRAL2, β=0.12, 88 MHz



In this talk :
LOW BETA = everything below 1 GHz



MYRRHA β=0.37, 352 MHz



ESS β=0.5, 352 MHz

OUTLINE

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  - Low temperature baking
  - Perspectives on nitrogen doping… is there one ?
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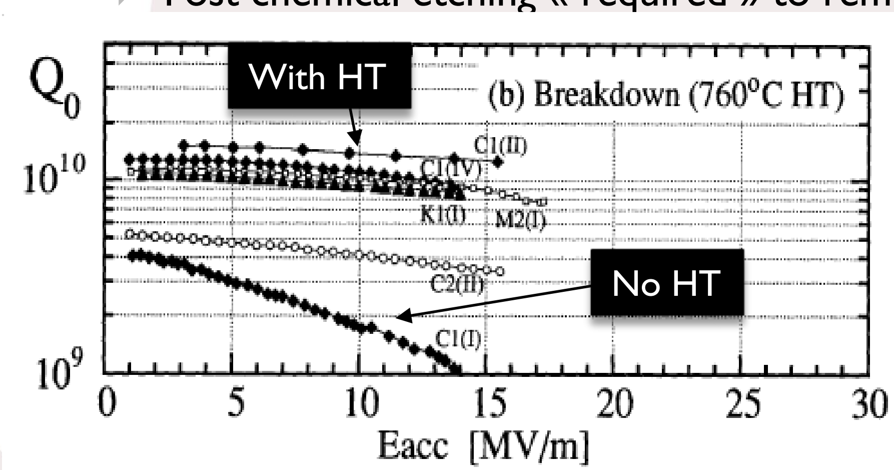
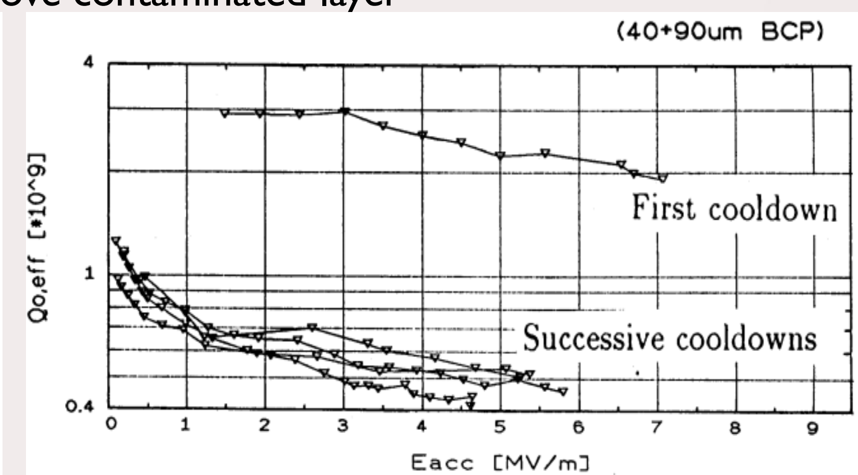
HEAT TREATMENTS

HYDROGEN DEGASSING history

- Aims at degassing hydrogen out of Niobium
  - Avoids Q-disease and irreversible degradation due to Q-disease
  - Decreases residual resistance and Q-slope
  - Releases mechanical stresses, recristalization
- But :
  - Require expensive dedicated furnace
  - Pollution of surface
    - Re-absorbtion of residual gas because oxide layer has been dissolved
    - Post chemical etching « required » to remove contaminated layer



« Test results on high gradient L-band superconducting cavities », E. Kako et al., Proceedings of the 6th SRF workshop, Newport News, USA, 1993



« Q degradation of niobium cavities due to Hydrogen contamination », B. Bonin and R.W. Röth, Proceedings of the 5th SRF workshop, Hamburg, Germany, 1991

HYDROGEN DEGASSING

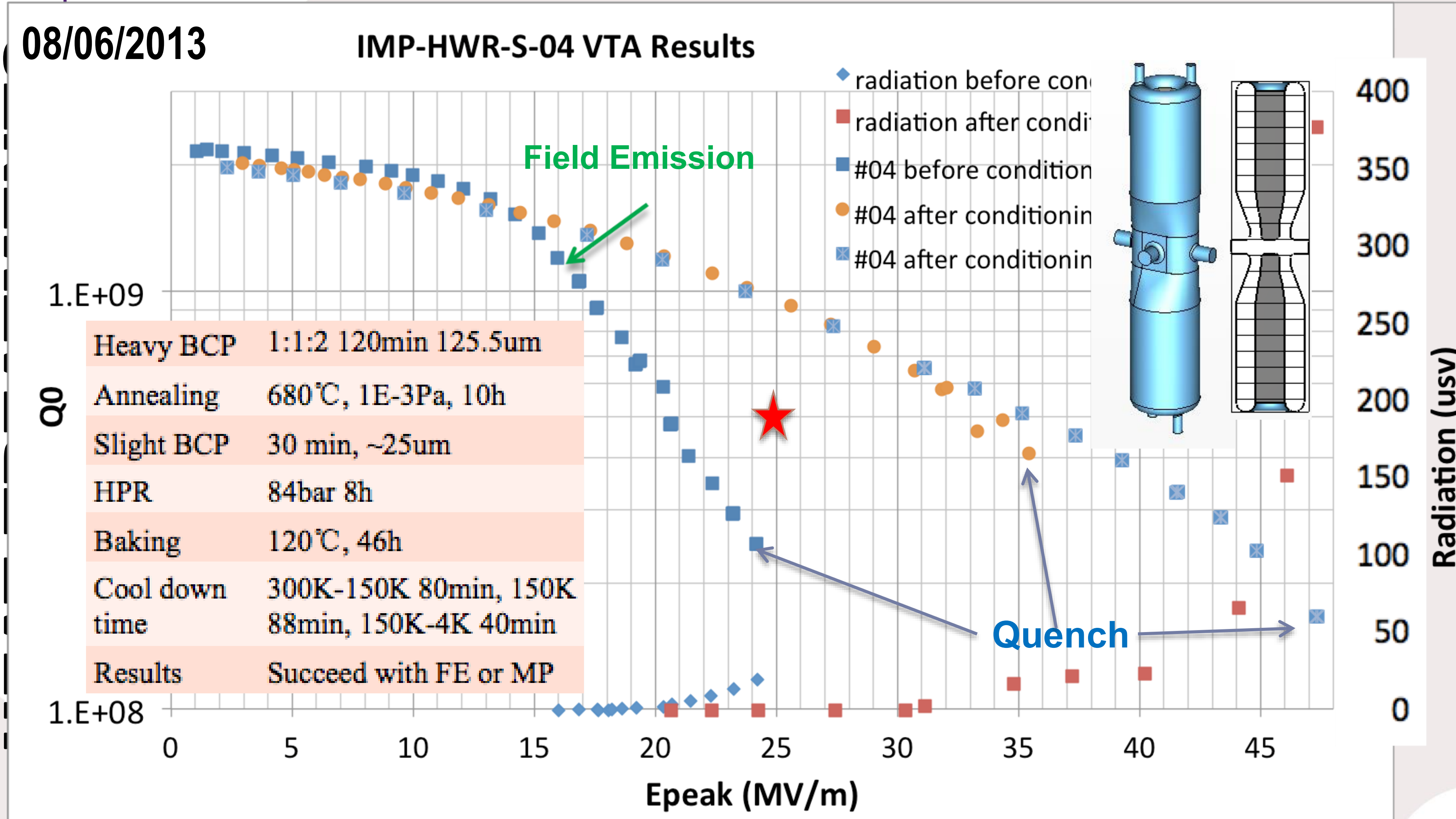
HEAT TREATMENTS

- 1.3 GHz elliptical cavity
  - Compulsory
    Irreversible degradation observed.
  - Done in standard preparation
  - Done with bare cavity
  - Typically at 800°C during 2-3h.
    Temperature limitation to limit recristalization and softening

- Low beta resonators
  - Not compulsory for QWR up to 170 MHz.
    Accelerators with non degassed cavities (ISAC2, ALPI, Saraf, Spiral2).
    Accelerators with degassed cavities (ATLAS, FRIB, C-ADS, IFMIF).
  - Looks compulsory for Spoke resonators at 352 MHz.
    Irreversible degradation observed in VT
  - Done with/without dressed cavity
  - Typically at 600°C - 650°C during 10h.
    Temperature limitation due to brazed stainless steel parts

HYDROGEN DEGASSING OF LOW BETA

- **Hydrogen degassing at IMP : Courtesy of W.Yue**



Heavy BCP	1:1:2 120min 125.5um
Annealing	680℃, 1E-3Pa, 10h
Slight BCP	30 min, ~25um
HPR	84bar 8h
Baking	120℃, 46h
Cool down time	300K-150K 80min, 150K 88min, 150K-4K 40min
Results	Succeed with FE or MP

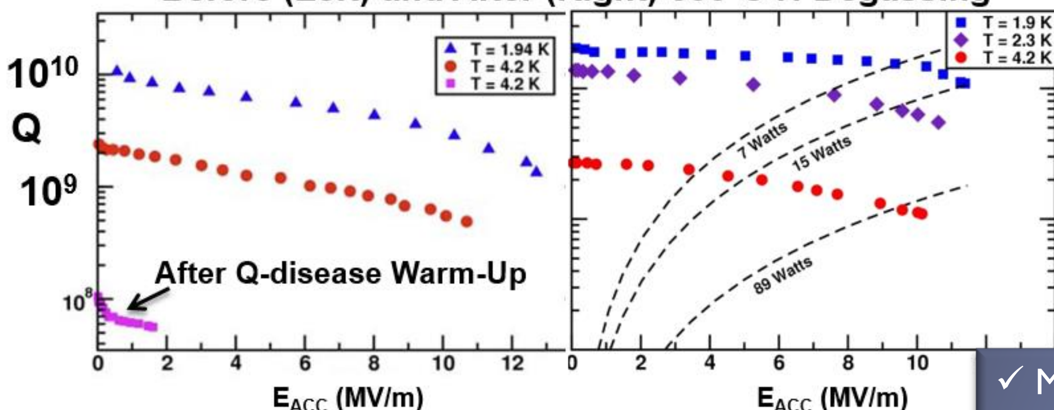
HYDROGEN DEGASSING OF LOW BETA

- **Hydrogen degassing at ANL : Courtesy of Z. Conway**

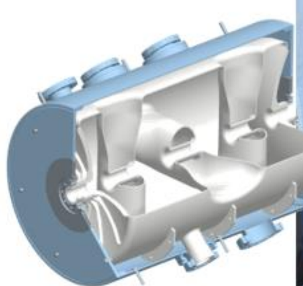
Results for 345 MHz Beta = 0.63 Triple Spoke Resonator

After Hydrogen Degassing, Performance Indicated that Cavities Should be Operated at 2 Kelvin

345 MHz β = 0.63 Resonator
Before (Left) and After (Right) 600⁰C H-Degassing



β=0.5 Triple-Spoke after electropolishing



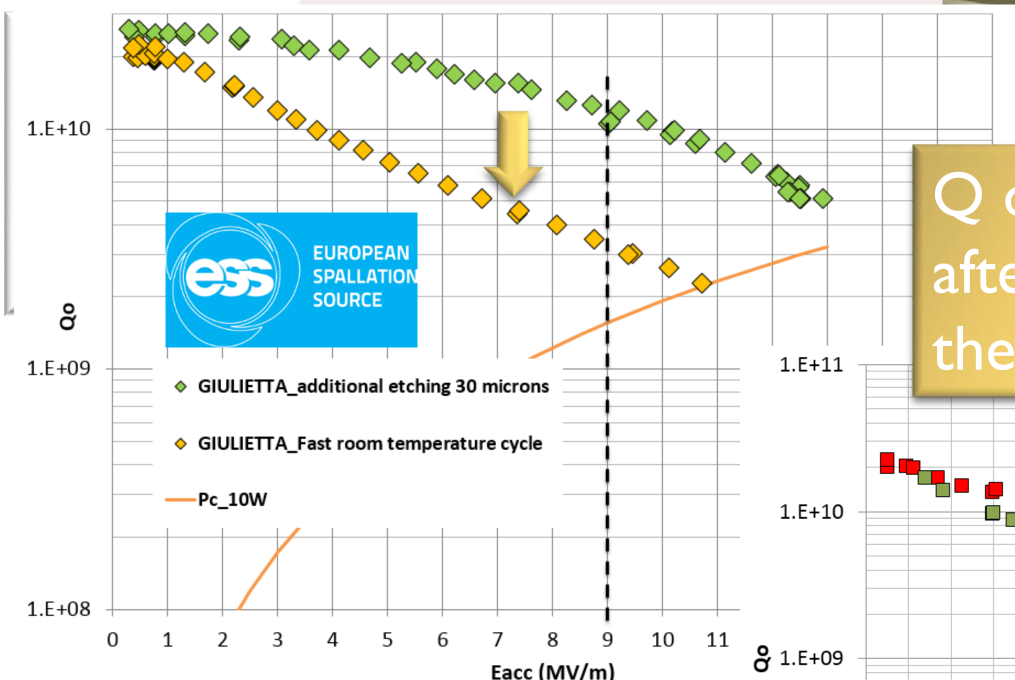
- ✓ Material : Bulk Niobium
- ✓ β = 0.63
- ✓ F_0 = 345 MHz
- ✓ T : 2K
- ✓ Bpk/Eacc = 9 mT/MV/m
- ✓ Epk/Eacc = 2.93
- ✓ G = 93

M. Kelly, SRF2005
K. Shepard, SRF2005

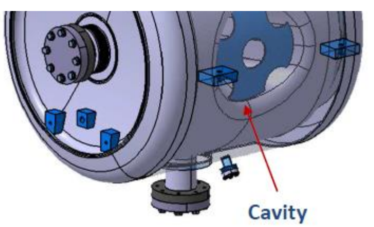
Argonne

HYDROGEN DEGASSING OF LOW BETA

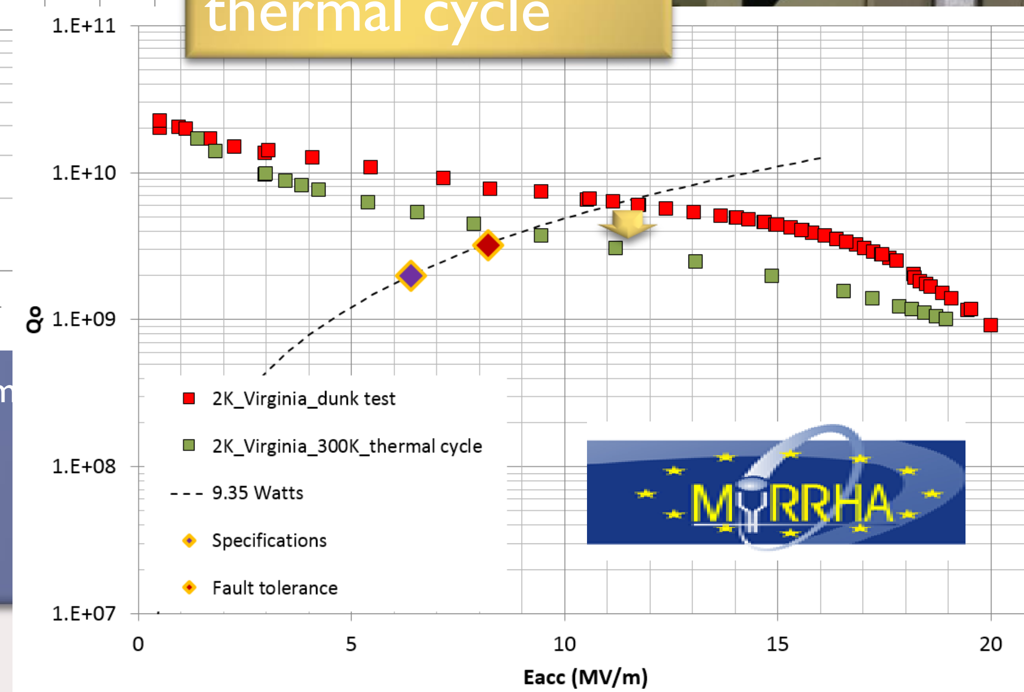
Hydrogen degassing at IPNO :



Q degradation after 300K thermal cycle



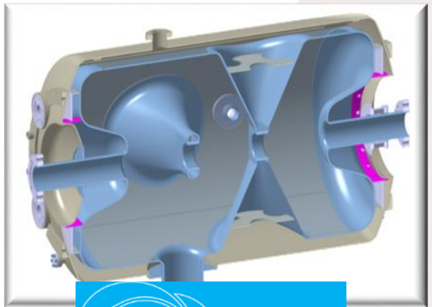
- ✓ T : 2K
- ✓ Eacc : 6.4 MV/m
- ✓ Bpk/Eacc = 7.3
- ✓ Epk/Eacc = 4.3
- ✓ r/Q = 217
- ✓ G = 109



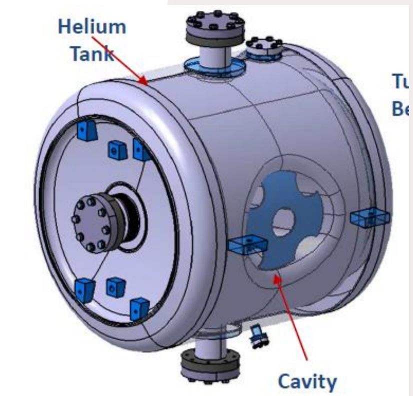
HYDROGEN DEGASSING OF LOW BETA

HEAT TREATMENTS

Hydrogen degassing at IPNO :



- ✓ Material : Bulk Niobium
- ✓ β = 0.5
- ✓ F_0 = 352 MHz
- ✓ T : 2K
- ✓ Eacc : 9 MV/m
- ✓ Bpk/Eacc = 6.9 mT/MV/m
- ✓ Epk/Eacc = 4.3
- ✓ r/Q = 426
- ✓ G = 130

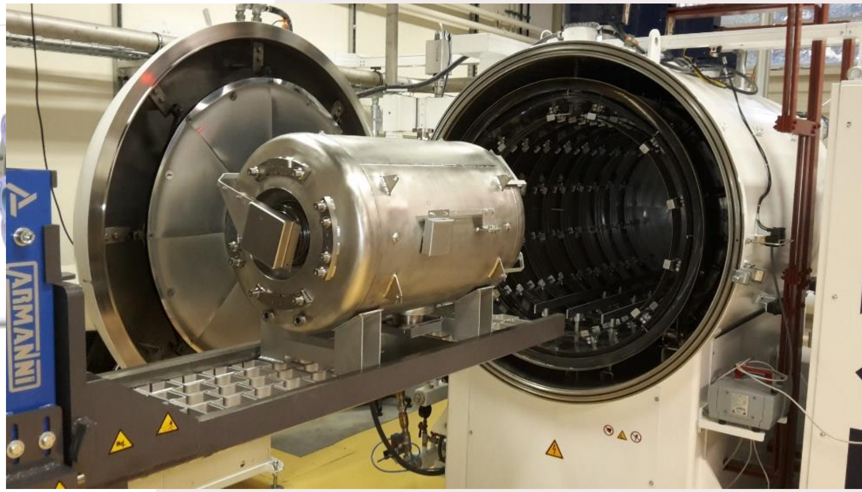


- ✓ Material : Bulk Niobium
- ✓ β = 0.37
- ✓ F_0 = 352 MHz
- ✓ T : 2K
- ✓ Eacc : 6.4 MV/m
- ✓ Bpk/Eacc = 7.3 mT/MV/m
- ✓ Epk/Eacc = 4.3
- ✓ r/Q = 217
- ✓ G = 109

Furnace commissioned in 2016

HYDROGEN DEGASSING OF LOW BETA

- **Hydrogen degassing at IPNO :**



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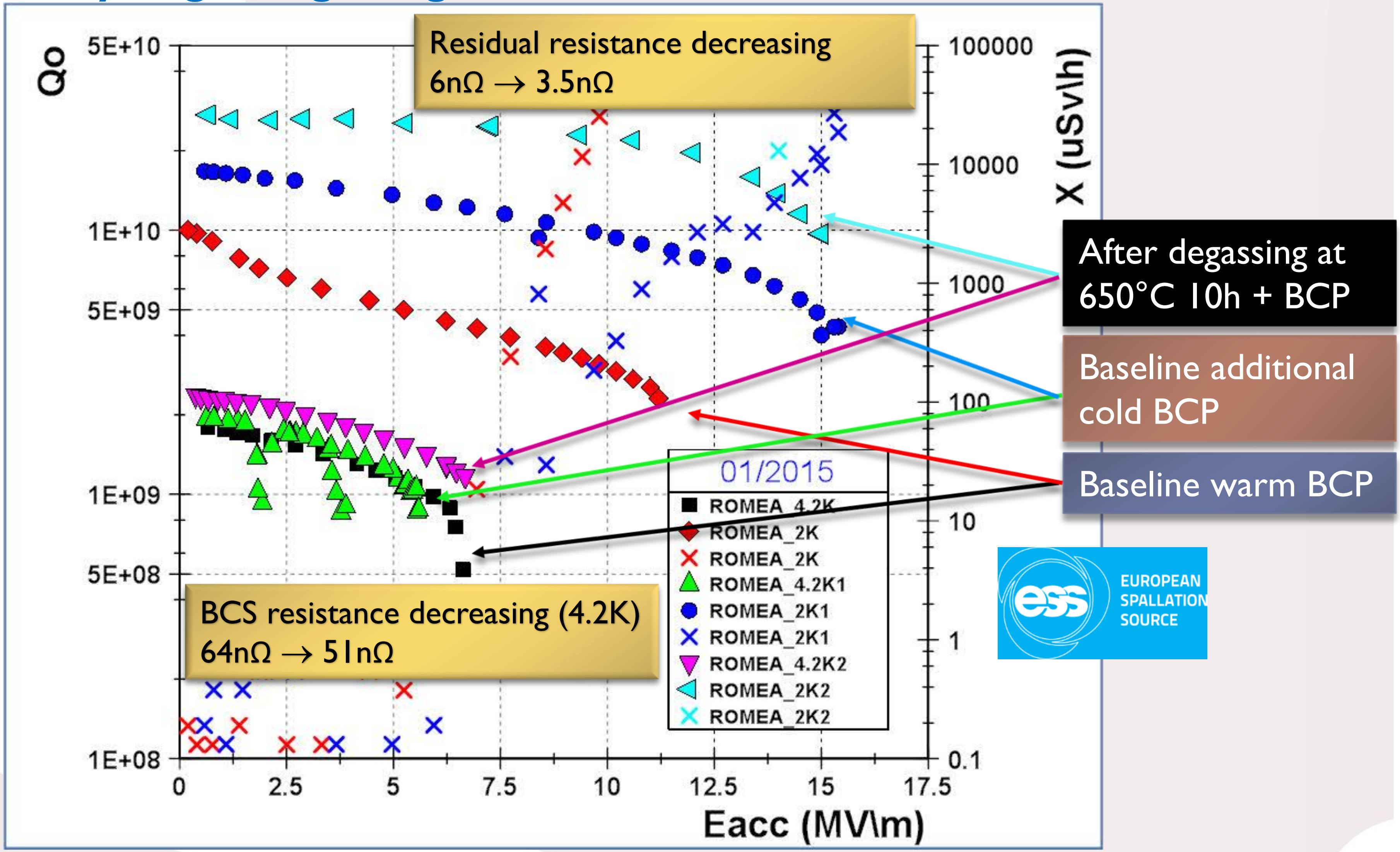

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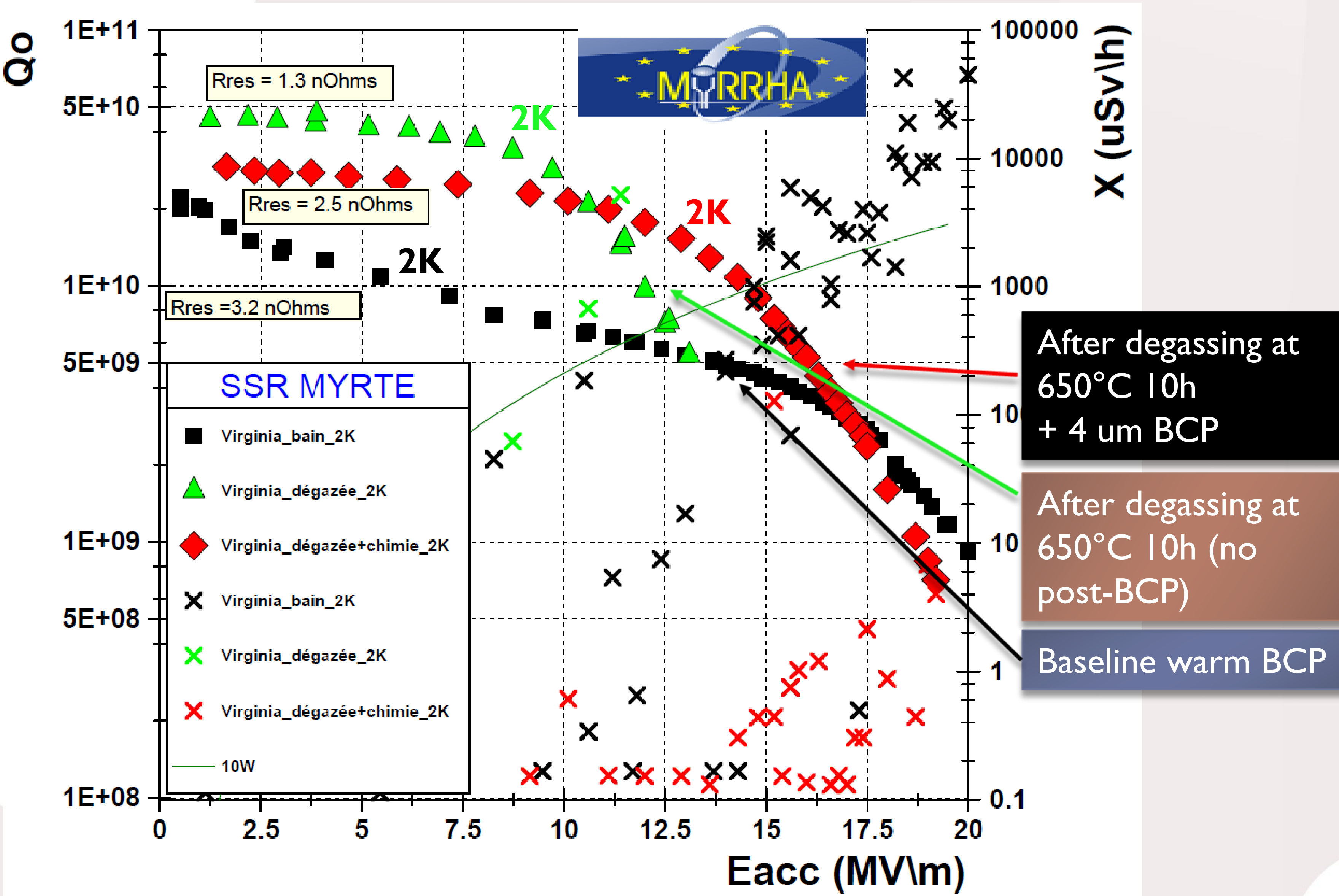
HEAT TREATMENTS



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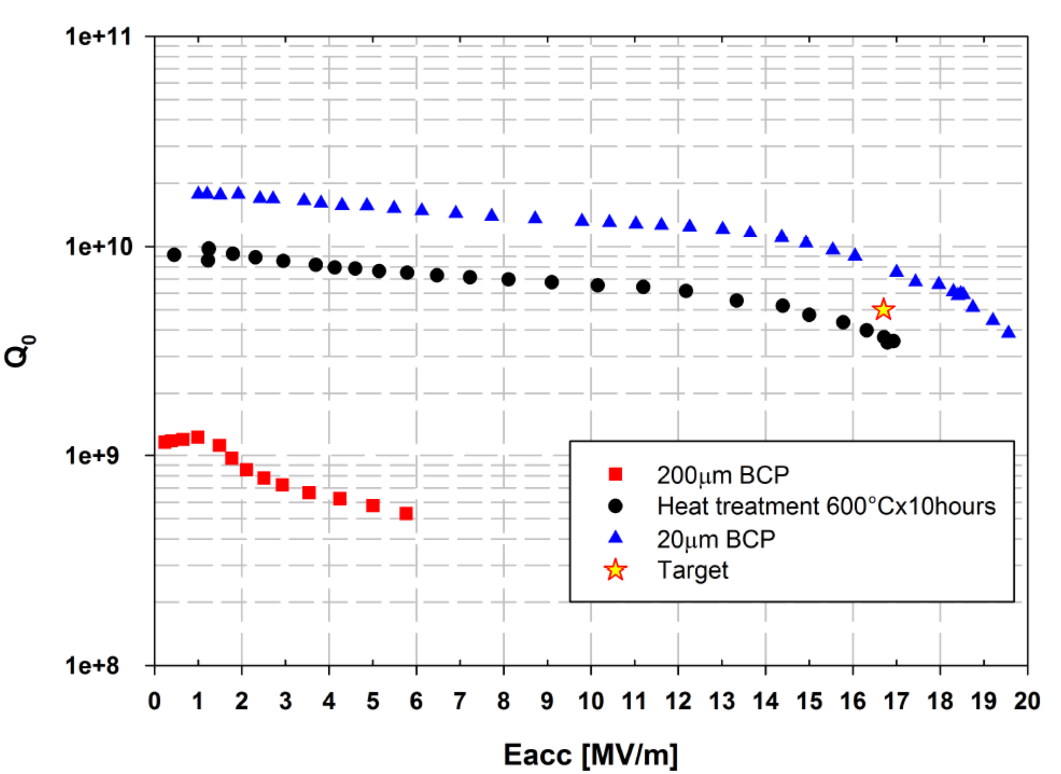
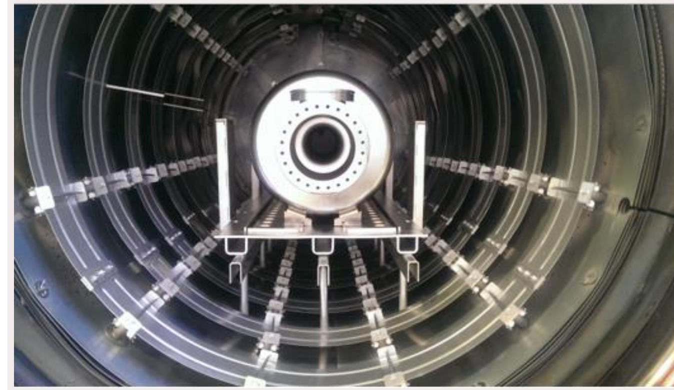
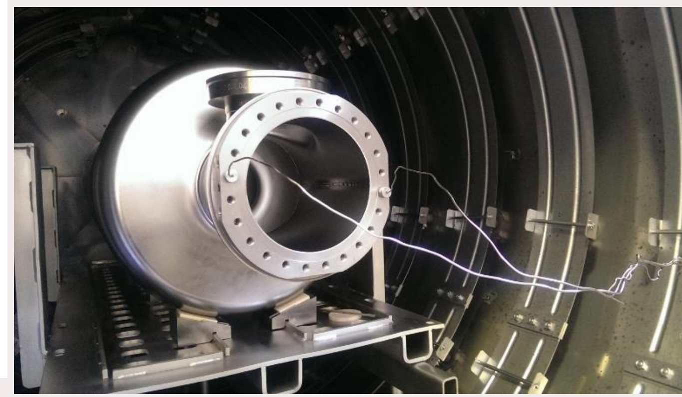
HEAT TREATMENTS







Treated at Zanon facility

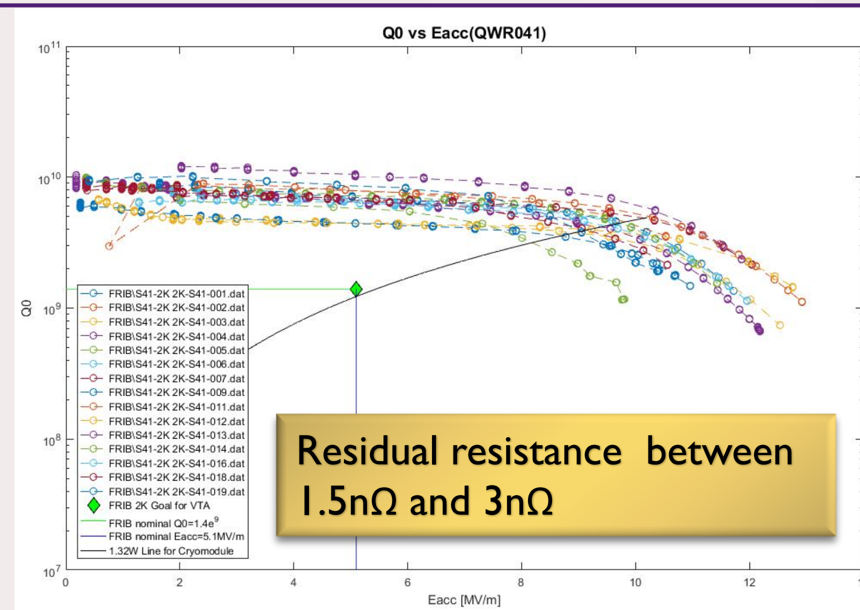
- ✓ Material : Bulk Niobium
- ✓ β = 0.67
- ✓ F_0 = 704 MHz
- ✓ T : 2K
- ✓ Bpk/Eacc = 4.8 mT/MV/m
- ✓Epk/Eacc = 3.8
- ✓G = 197

COURTESY OF E. CENNI, CEA

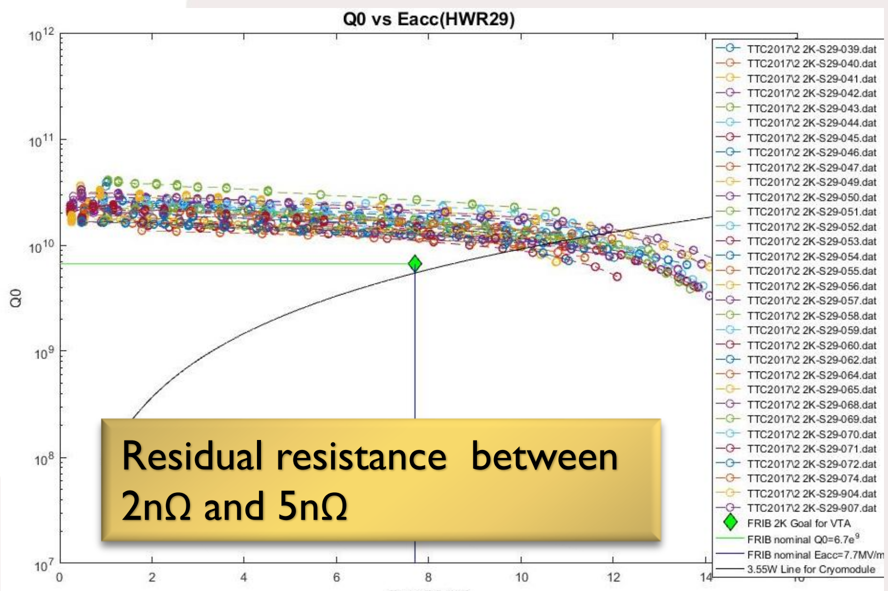
HYDROGEN DEGASSING OF LOW BETA

HEAT TREATMENTS

- FRIB example after degassing
- Unfortunately no data before hydrogen degassing for comparison



Residual resistance between 1.5nΩ and 3nΩ



Residual resistance between 2nΩ and 5nΩ

K. Saito, February 2017 TTC201702

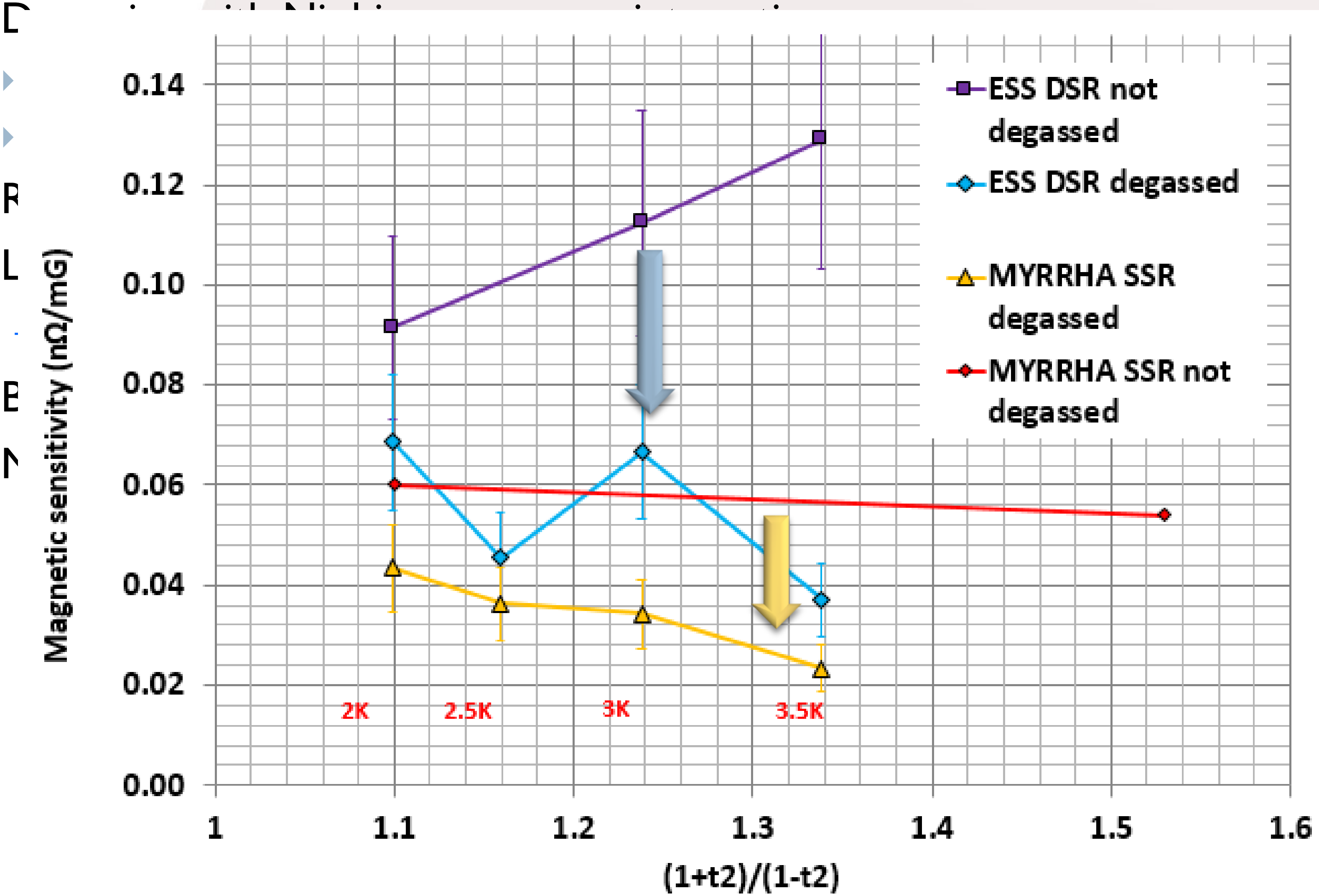
HYDROGEN DEGASSING OF LOW BETA

- Degassing with Niobium caps very interesting
  - No post etching required
  - Allow alternative treatment like N2 infusion
- Residual resistance is decreased → No hydrogen precipitation
- Linear dependence of Q-slope is eliminated
  → Disparition of Josephson weak links [*]
- BCS resistance is decreased as well → « doping of Niobium », RRR ↓
- Magnetic sensitivity is decreased
  → Observed on elliptical cavities
  → And also on Spoke cavities at 352 MHz

$$R_{BCS} = \frac{A \cdot \omega^2}{T} \cdot \exp\left(\frac{-\Delta}{k_B \cdot T}\right)$$

HYDROGEN DEGASSING OF LOW BETA

HEAT TREATMENTS



OUTLINE

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  - Perspectives on nitrogen doping… is there one ?
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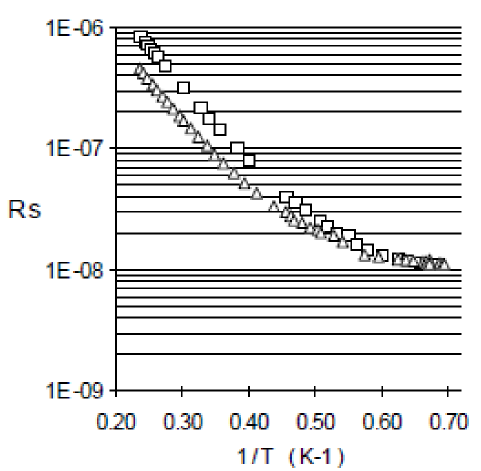
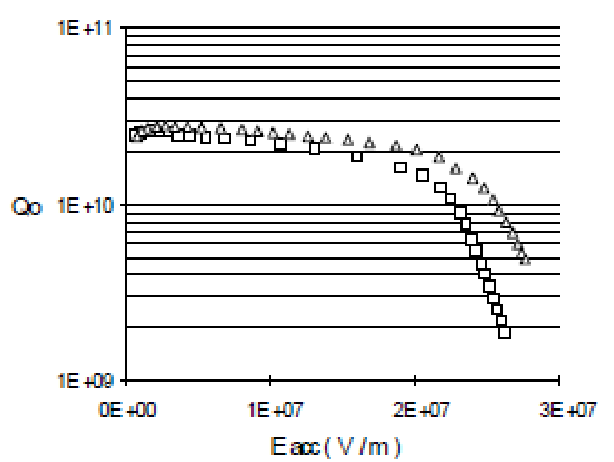
Low temperature baking for elliptical cavities

HEAT TREATMENTS

- Most of labs converged toward 120°C during 48h
- Aims at removing the high field Q-slope
  - First reported by B.Visentin in1998.
  - Decreases BCS resistance
  - Decreases (for BCP cavity) or eliminates (for EP cavity) the high field Q-slope
  - Could be used to accelerate drying of cavity
- But :
  - Increases residual resistance

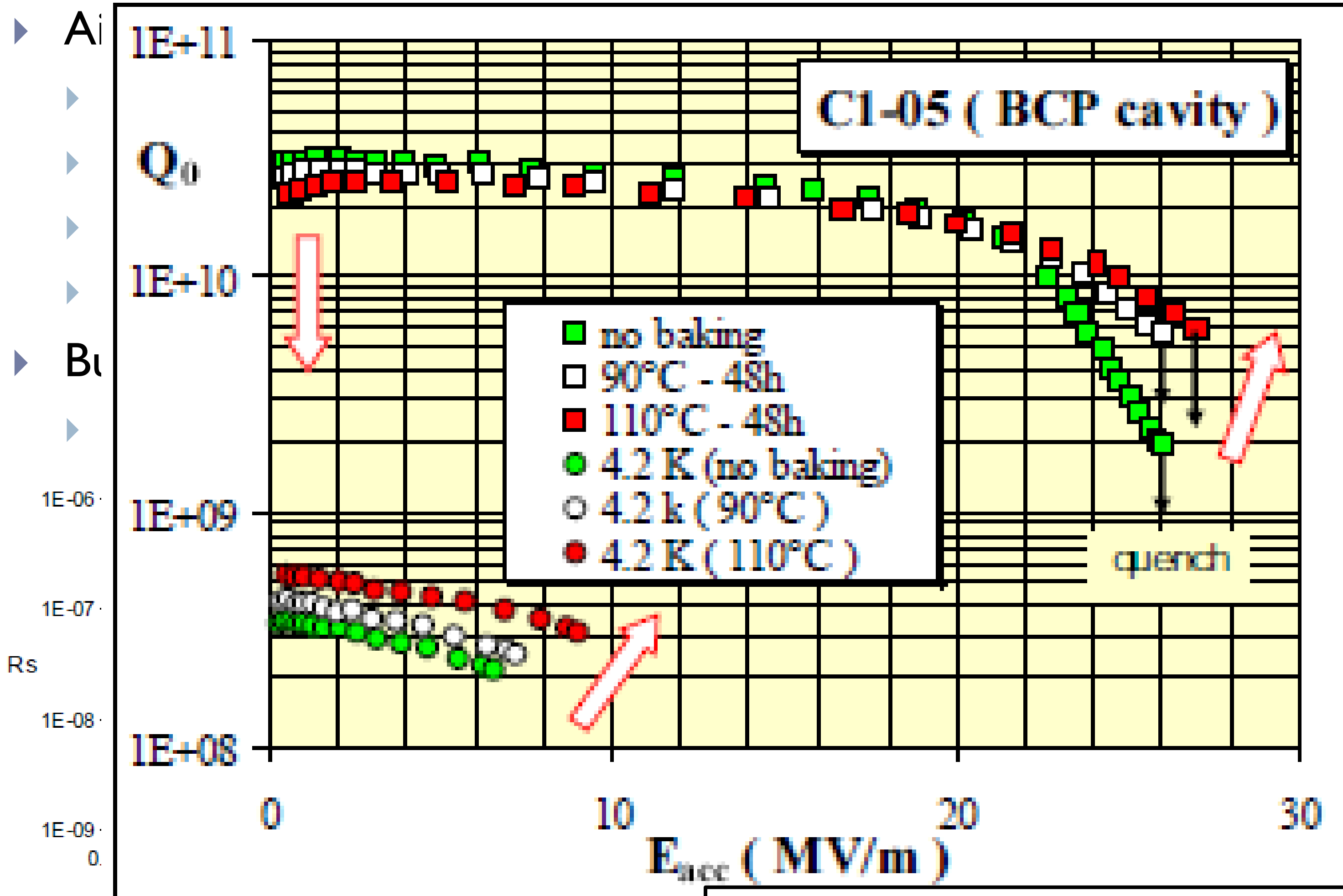




«Improvements of superconducting cavity performances at high accelerating gradients », B. Visentin et al., Proc EPAC 1998, p. 1885

Low temperature baking for elliptical cavities

- Most of labs converged toward 120°C during 48h
- Ai
  - Q-slope
- Bu



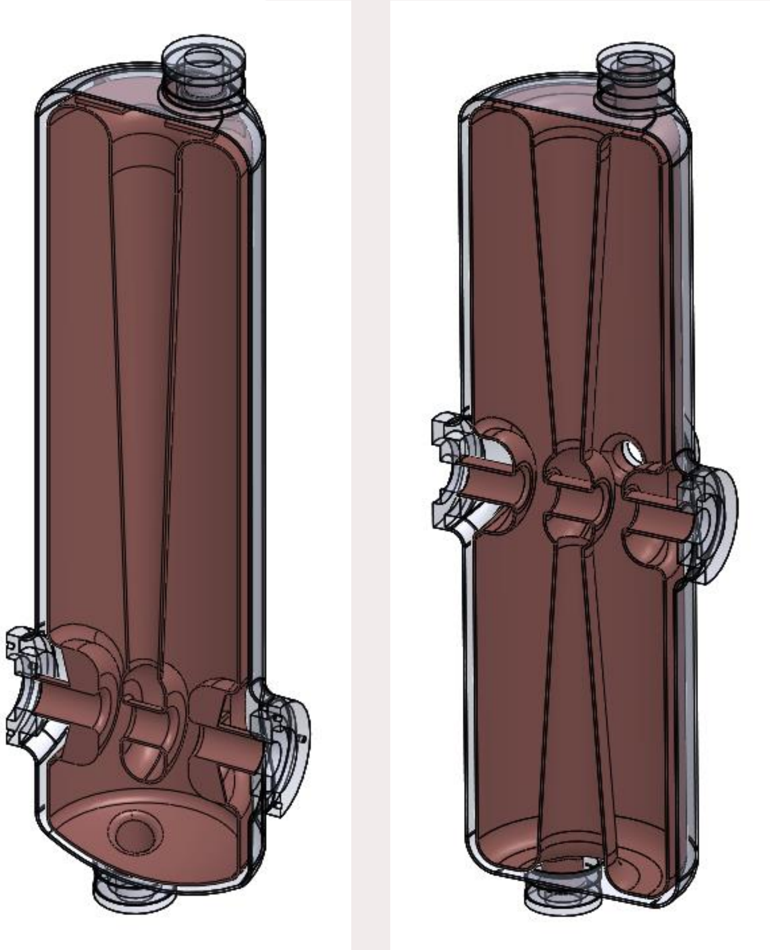
«Improvements of superconducting cavity performances at high accelerating gradients », B. Visentin et al., Proc EPAC 1998, p. 1885

«Q-slope at high gradients : review of experiments and high gradient », B. Visentin, Proceedings of the 11th SRF workshop, Lübeck, Germany, 2003

HEAT TREATMENTS

Low temperature baking of low beta

Baking for RISP :



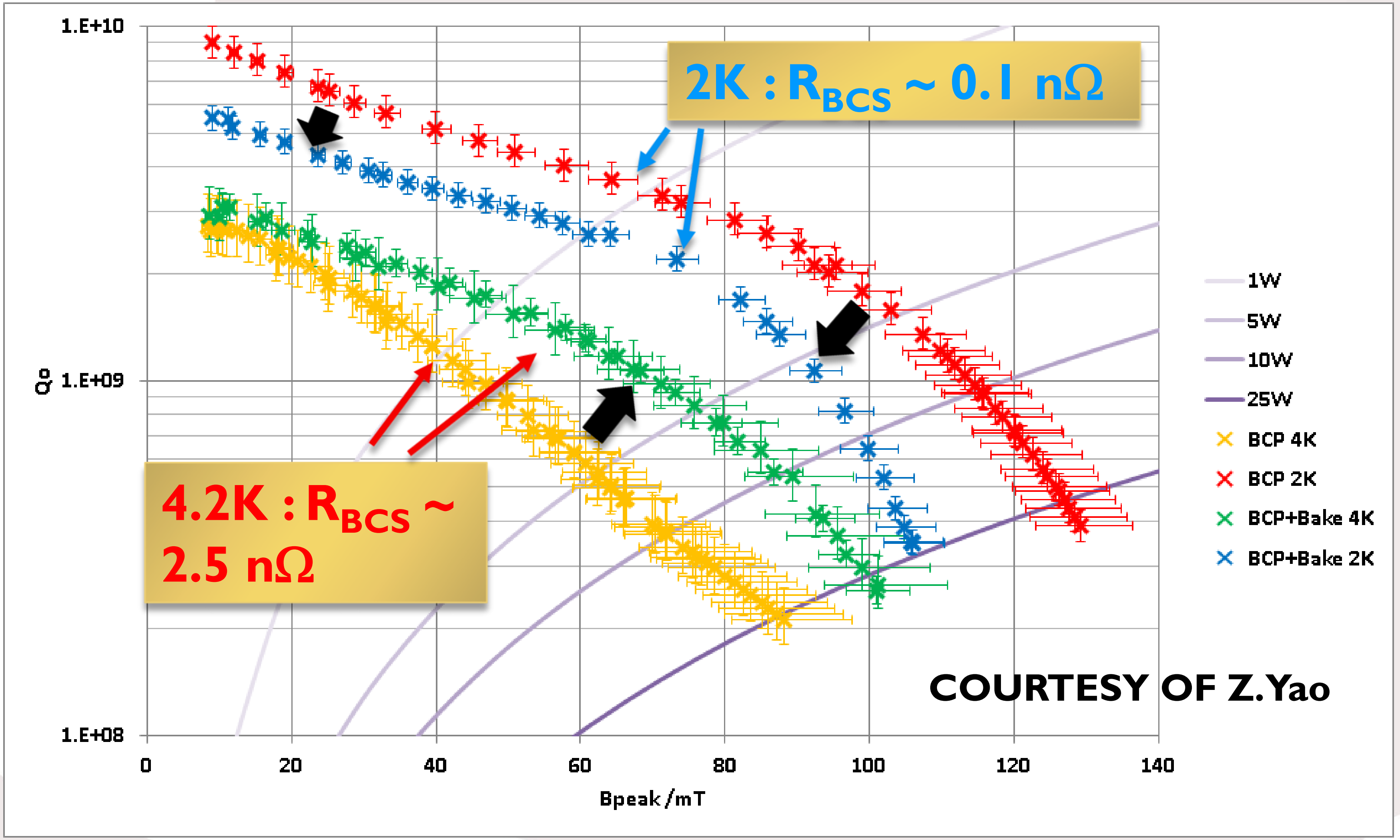
COURTESY OF Z. Yao

- **81.25MHz QWR and 162.5MHz HWR designed by RISP.**
- **Cavity treatments**
  - **120µm BCP (+15µm for HWR)**
  - **HPR**
  - **48hr 120°C bake**
- **Cavities were tested before and after bake.**

	QWR	HWR	Unit
Frequency	81.25	162.5	MHz
β	0.047	0.12	1
$L_{eff}=\beta\lambda$	0.173	0.221	m
E_{peak}/E_{acc}	5.3	5.6	1
B_{peak}/E_{acc}	9.5	8.2	mT/MV/m
G	21	40	Ω
U/E_{acc}^2	0.126	0.159	$J/(MV/m)^2$

Low temperature baking of low beta

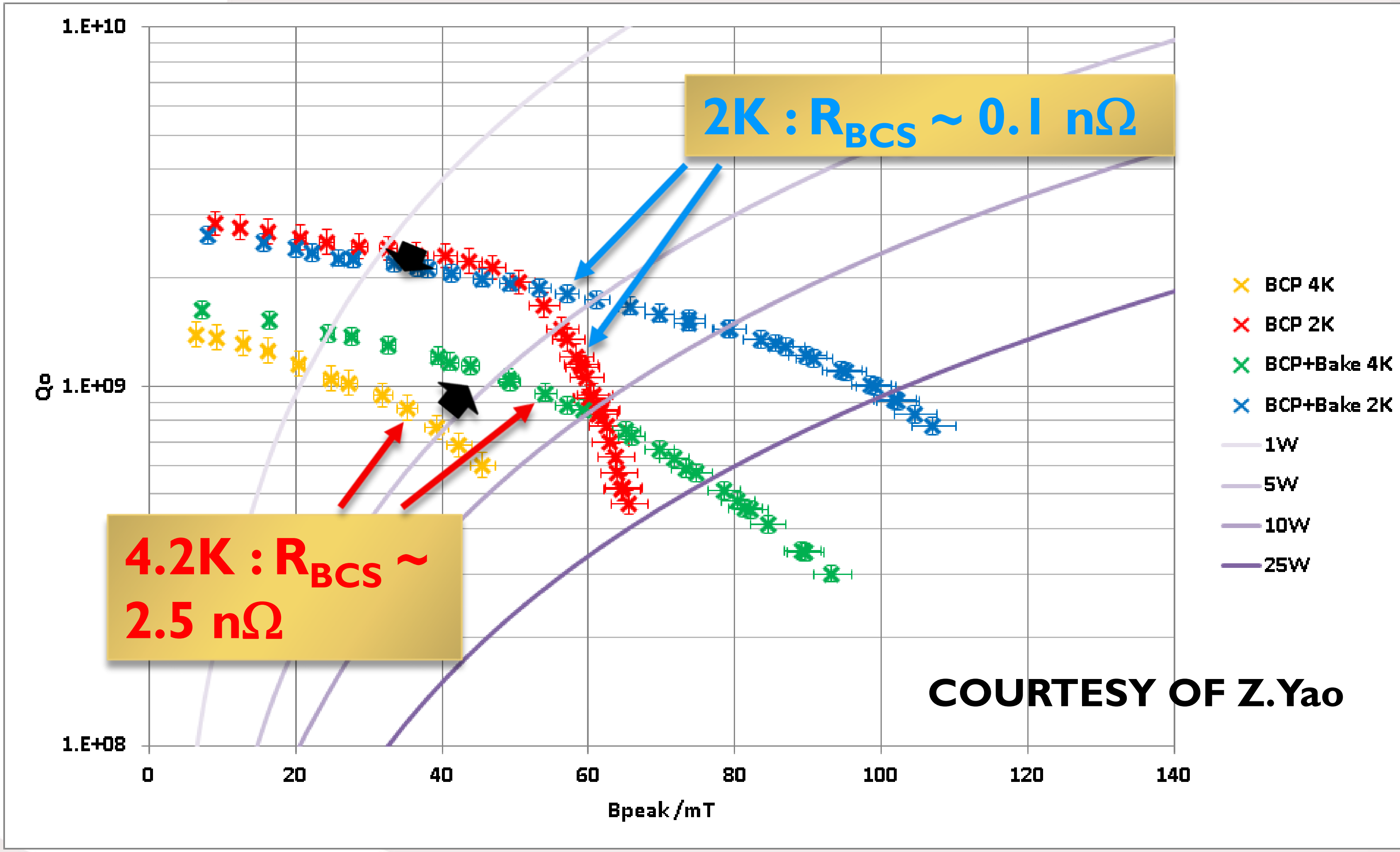
- Baking for RISP : 81 MHz QWR



Low temperature baking of low beta

HEAT TREATMENTS

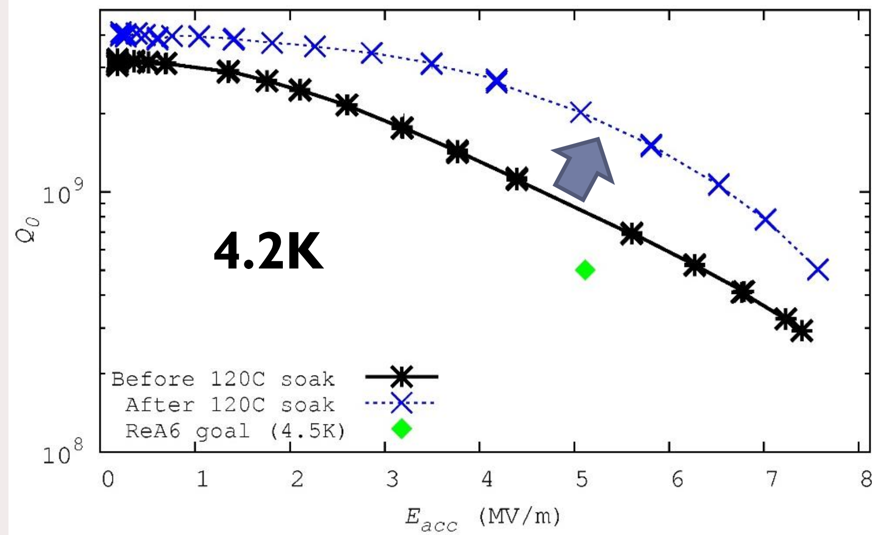
Baking for RISP : 162 MHz HWR

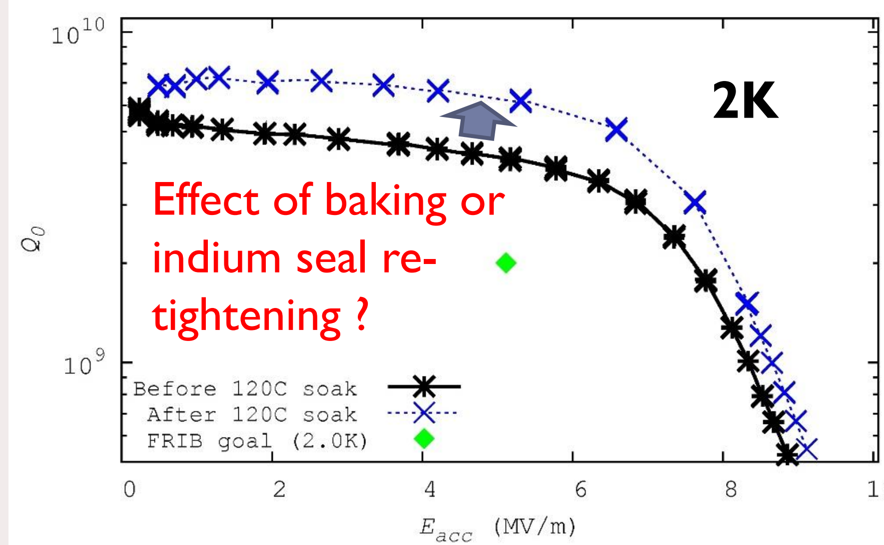


Low temperature baking of low beta

HEAT TREATMENTS

- **Baking at 120°C during 48h at FRIB : 80.5 MHz QWR**

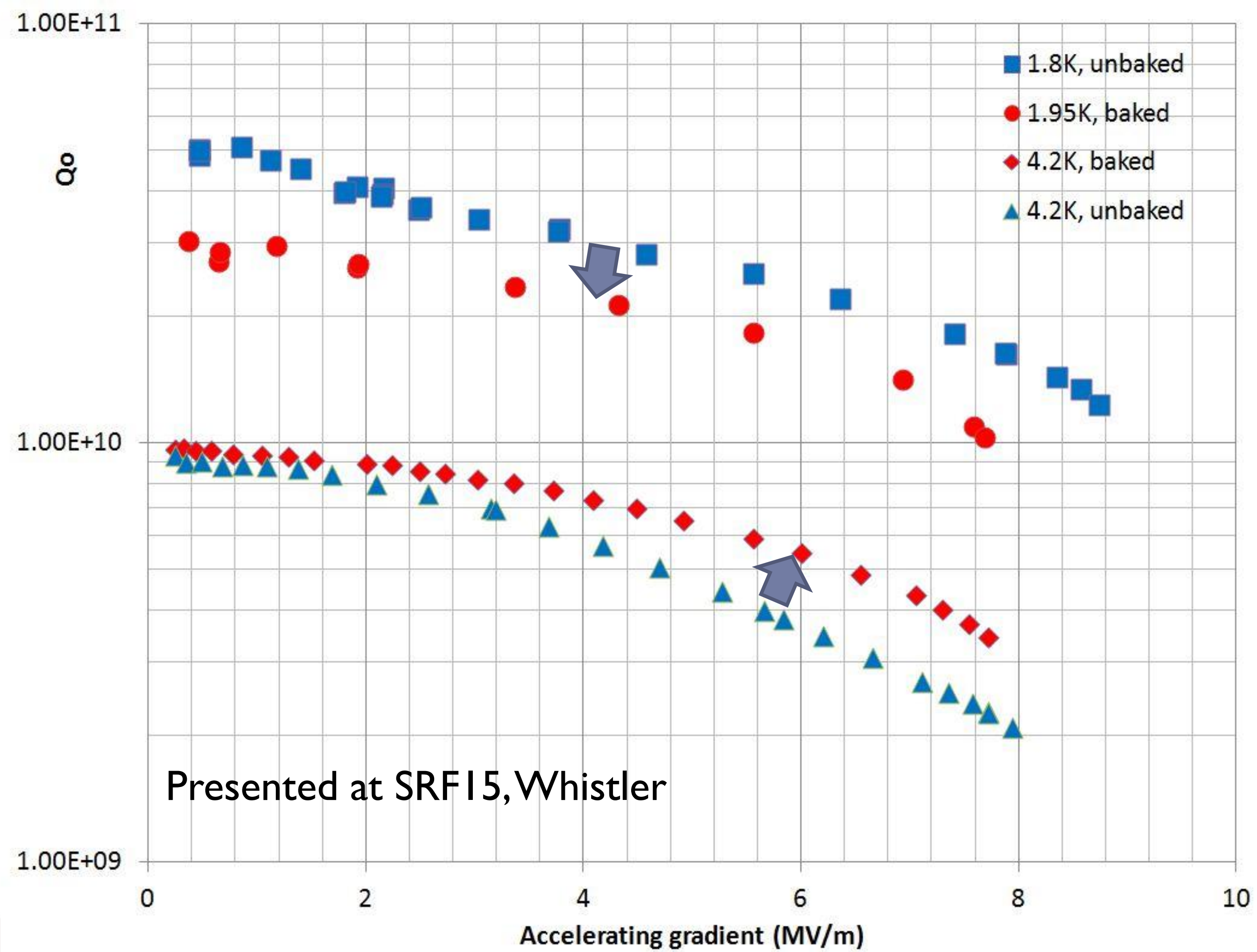




Presented at TTC meeting by J. Popielarski, december 2011

Low temperature baking of low beta

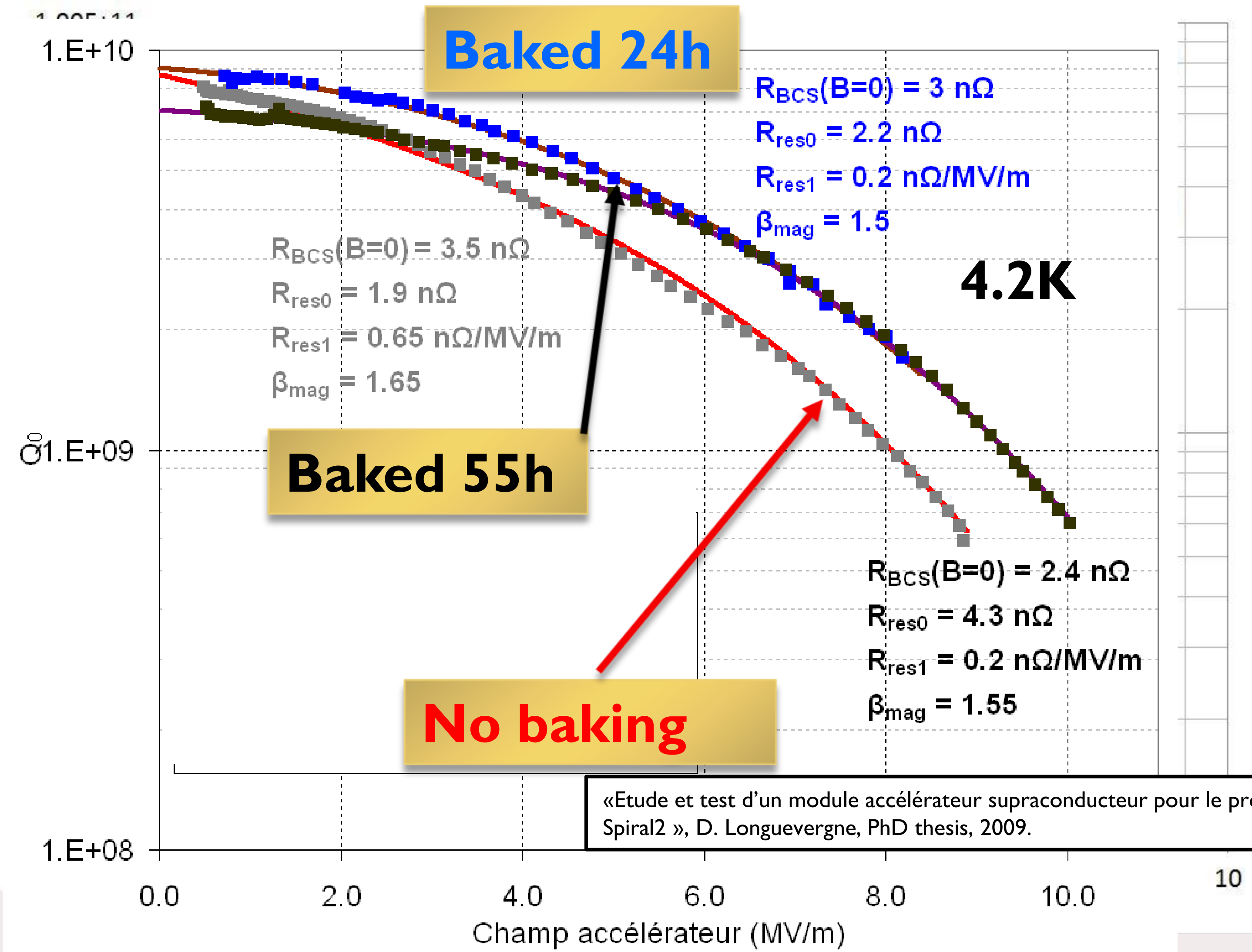
- **Baking at 120°C at IPNO : 88 MHz QWR**



HEAT TREATMENTS

Low temperature baking of low beta

- **Baking at 120°C at IPNO : 88 MHz QWR**



«Etude et test d'un module accélérateur supraconducteur pour le projet Spiral2 », D. Longuevergne, PhD thesis, 2009.

Low temperature baking of low beta

- Residual resistance is increased → diffusion of surface impurities
- BCS resistance is decreased → reduction of electron mean free path
- 4.2 K Q-slope is decreased → origin of Q-slope is BCS
- Difference between elliptical and low beta :
  - **For elliptical cavities** : baking affects only the high field Q-slope (>20 MV/m)
  - **For low beta cavities** : Q-slope impacted at low field

Cavity	Frequency	Pre-treatment	Residual resistance	BCS resistance
QWR RISP	81.25 MHz	BCP	↑	↓
HWR RISP	162.5 MHz	BCP	↑	↓
QWR ReA3	80.5 MHz	BCP + 600°C degassing	↓ ??	↓
QWR Spiral2	88 MHz	BCP	↑	↓

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N_2 « doping » for elliptical cavities

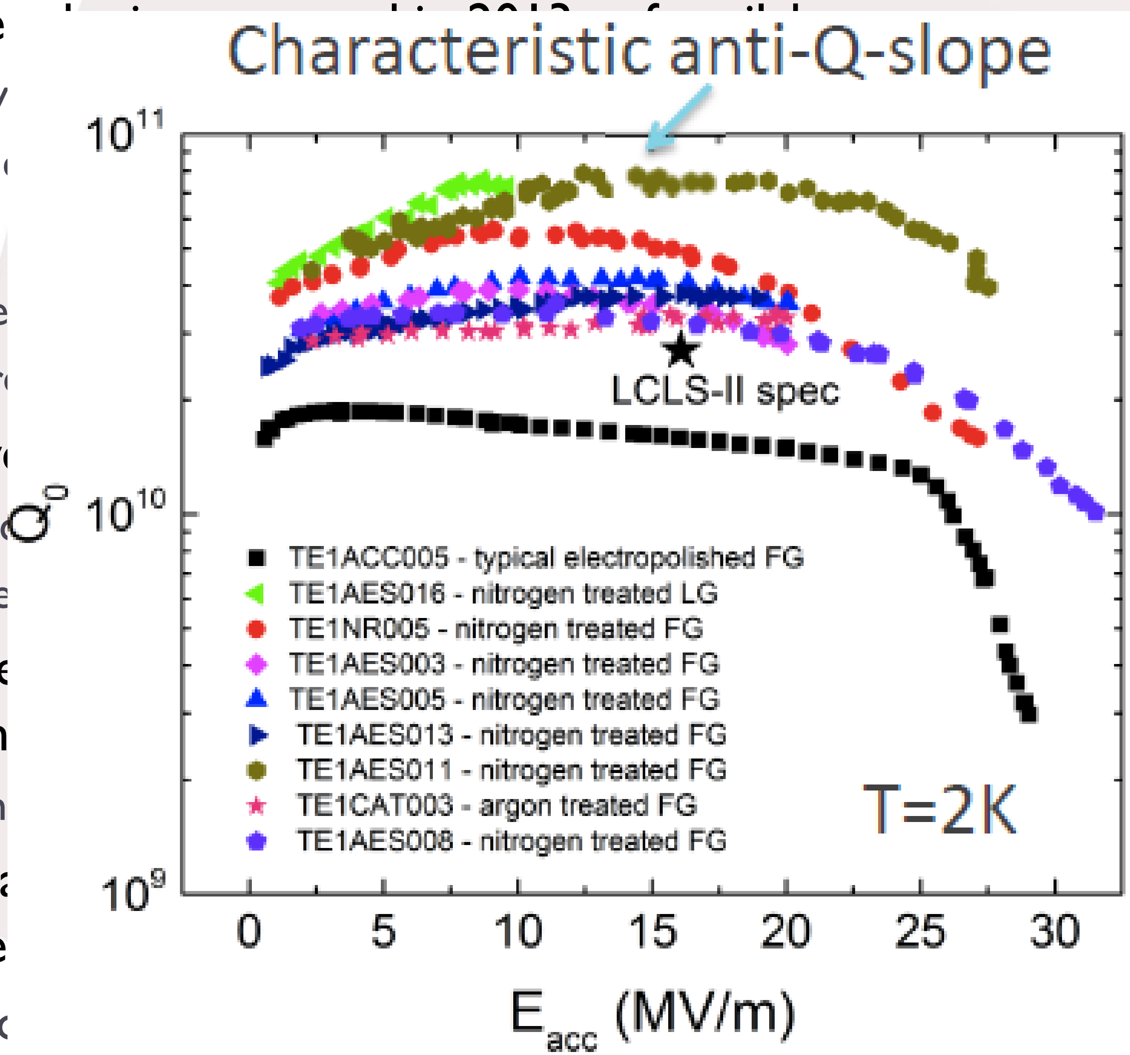
Perspectives on nitrogen doping

- Nitrogen doping reported in 2013 at fermilab
  - Cavity exposed to nitrogen gas at the end of thermal cycle at 800° C
  - Small chemical etching required to remove over-doped layer
- Positive effects :
  - Decrease of BCS resistance
  - BCS resistance is improving with accelerating gradient (anti Q-slope)
- Negative effects :
  - Quenching gradient is reduced
  - Magnetic sensitivity is drastically increased
- Heat treatment (300° C to 800° C) with N_2/Ar refill already tried by B. Visentin in 2001
  - Anomalously low BCS resistance observed. No mention of anti Q-slope
- G. Ciovatti reported nitridization treatment at 400° C following a 800° C treatment in 2010
  - Improvement of residual resistance

N_2 « doping » for elliptical cavities

Perspectives on nitrogen doping

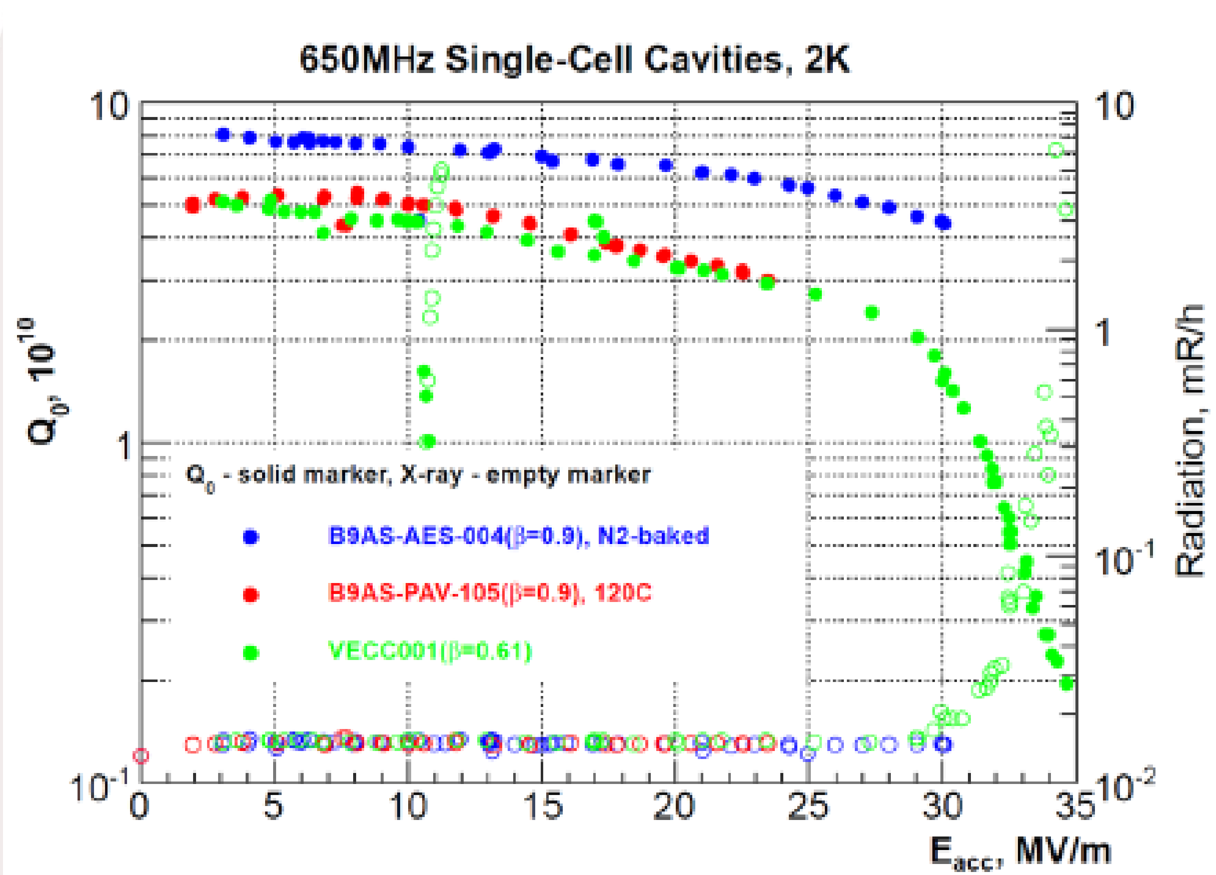
- Nitroge
  - Cavity … C
  - Small (
- Positive
  - Decre
  - BCS r …)
- Negativ
  - Quen
  - Magne
- Heat tre … y tried by B. Visentin
  - Anom … ope
- G. Ciova … ving a 800° C treatme
  - Impr



A. Grassellino et al, 2013 Supercond. Sci. Technol. 26 102001 (Rapid Communication)

N_2 « doping » for low beta

- Only one example at 650 MHz



CAVITY PROCESSING AND PREPARATION OF 650 MHz ELLIPTICAL CELL CAVITIES FOR PIP-II*, A. M. Rowe et al., Proceedings of LINAC2016, East Lansing, US.

N_2 « doping » for low beta

- Nitrogen doping keeps residual resistance low and decreases BCS resistance
- To be beneficial residual resistance has to be low compaired to BCS resistance
- What does that mean for low beta cavities :
  - If operated at 2K
    - No point to dope up to 500 MHz, as BCS resistance is low and MFQS is negligeable
  - If operated at 4.2K
    - Worth doing it especially if Q-slope is from BCS and not residual resistance

- Could nitrogen doping allow 4.2K operation of Spoke cavities at 352 MHz ?

R_{BCS} (nΩ)	4.2K	2K	1.8K	1.5K
1300 MHz	585	15	6.5	1.2
700 MHz	174	4.3	1.9	0.35
352 MHz	44	1	0.5	0.09
176 MHz	11	0.3	0.1	0.02
88 MHz	3	0.07	0.03	0.006

CONCLUSION

	1.3 GHz Elliptical	Observed improvements	Low beta cavities
Hydrogen degassing	- Compulsory - Done without tank - Done at 800°C - Done during 3h	- Improvement of Residual - Improvement of BCS - Improvement of Q-slope - Q-disease disappears	- Not compulsory below 300 MHz - Done with/without tank - Brazed parts → done at 600°C - Done during 10h
120°C baking	- Done during 48h - Hot air/nitrogen blown around cavity	- Improvement of BCS - Degradation of Residual - Improves HFQS (1.3 GHz Elliptical) / - Improves MFQS (Low beta cavities)	- Done during 48h - Hot air blown in helium tank - Heating wires
Nitrogen doping	- 800°C 3h + 2 min at 25 mtorr N_2 + 6 min in UHV + EP - 800°C 3h + 160°C at 25 mtorr N_2 during 48h	- Improvement of BCS resistance - Residual resistance stays constant - Anti Q-slope (1.3 GHz Elliptical) / - No anti Q-slope (Low beta cavities)	- Tried on 650 MHz only - Will be tried on Spoke at 352 MHz

CONCLUSION

THANKS A LOT FOR YOUR ATTENTION

AND MANY THANKS FOR PROVIDING MATERIAL TO :

- Zack Conway, ANL
- Zhongyuan Yao, TRIUMF/RISP
- Yue Weiming, IMP
- Enrico Cenni, CEA

THE BCS RESISTANCE

$$R_{BCS} = \frac{8 \cdot 10^{-5}}{T} \cdot f^{2} \cdot \exp\left(-\frac{1.83 \cdot Tc}{T}\right)$$

R_{BCS} (nΩ)	4.2K	2K	1.8K	1.5K
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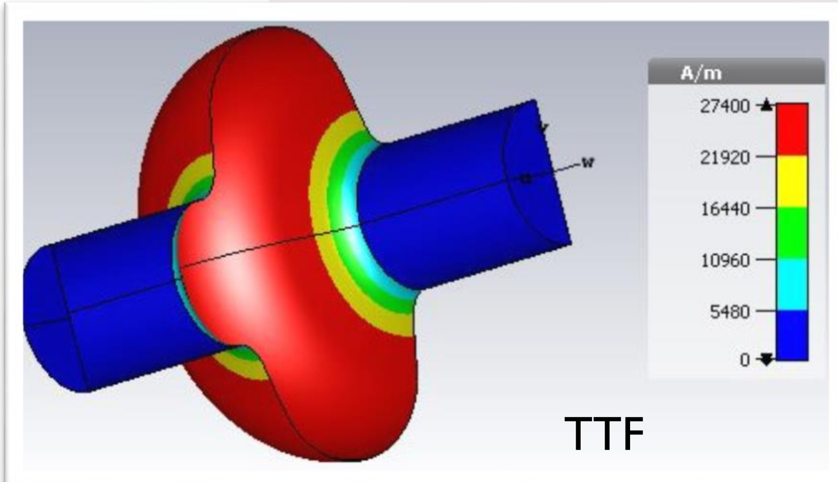
Cavity	Frequency	Residual (nΩ)		A (10^{-5} nΩ K/s^{-2})	
		Before HT	After HT	Before HT	After HT
QWR FRIB	80.5 MHz	X	1.5	X	7
Spoke ANL	345 MHz	6.5	4.5	7	6
Spoke IPNO	352 MHz	3.2	1.3 (no BCP)	9.5	8
Elliptical ESS	704 MHz	150	6	15	12.5
Elliptical KEK [**]	1.3 GHz	60	10	X	X

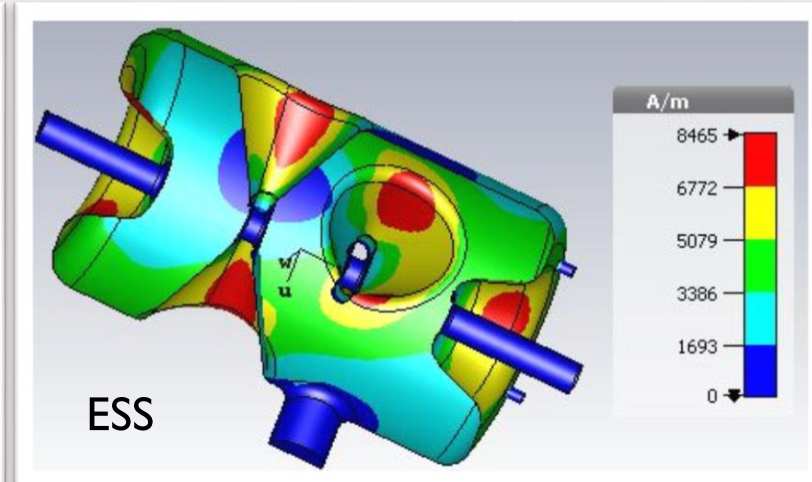
[*] : « Additional losses in high purity niobium cavities related to slow cooldown and hydrogen segregation », J. Halbritter et al., Proceedings of the 6th SRF workshop, Newport News, USA, 1993

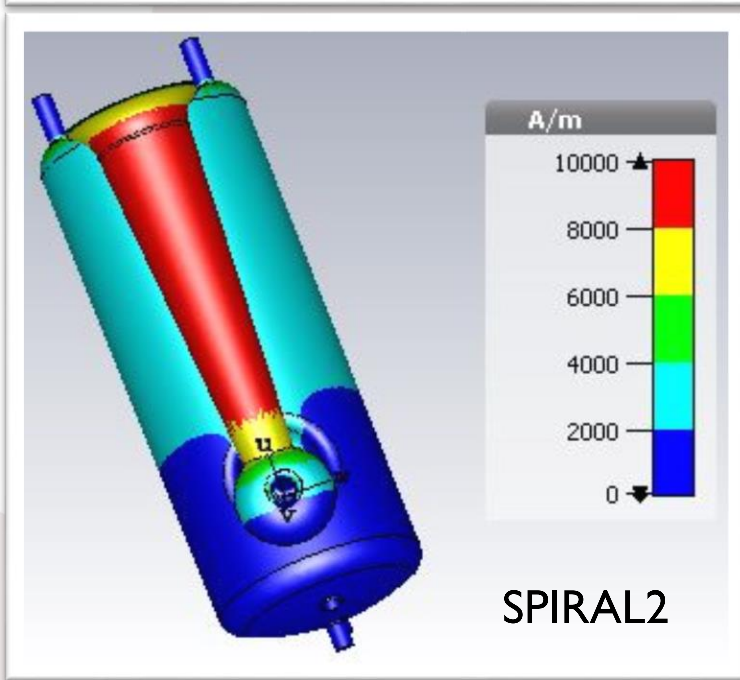
« Test results on high gradient L-band superconducting cavities », E. Kako et al., Proceedings of the 6th SRF workshop, Newport News, USA, 1993

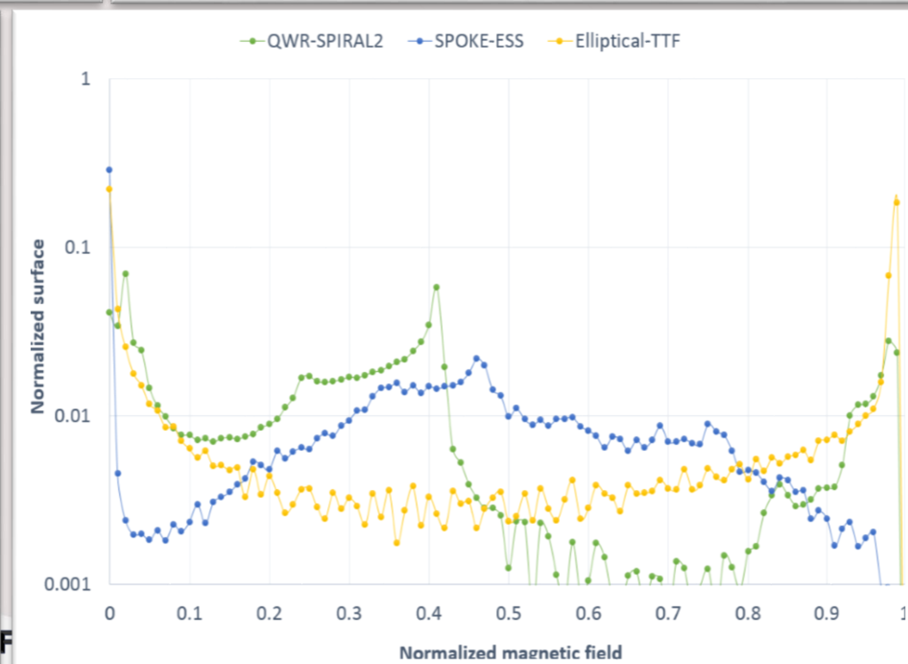
FIELD DISTRIBUTION

- Field distribution very different depending on the geometry





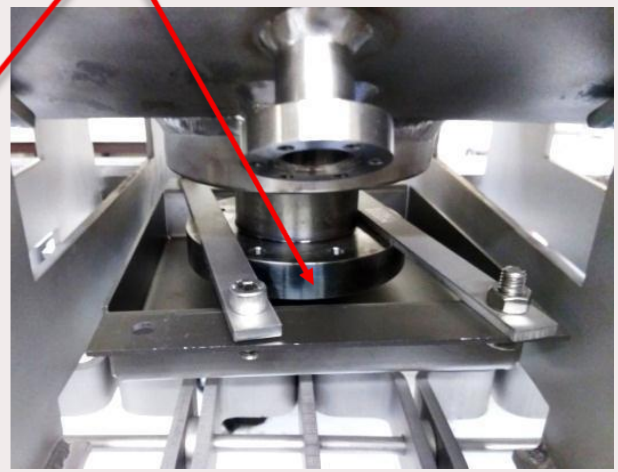




R&D for MYRRHA : MYRTE program

Sample study

- Niobium samples have been installed in cavity

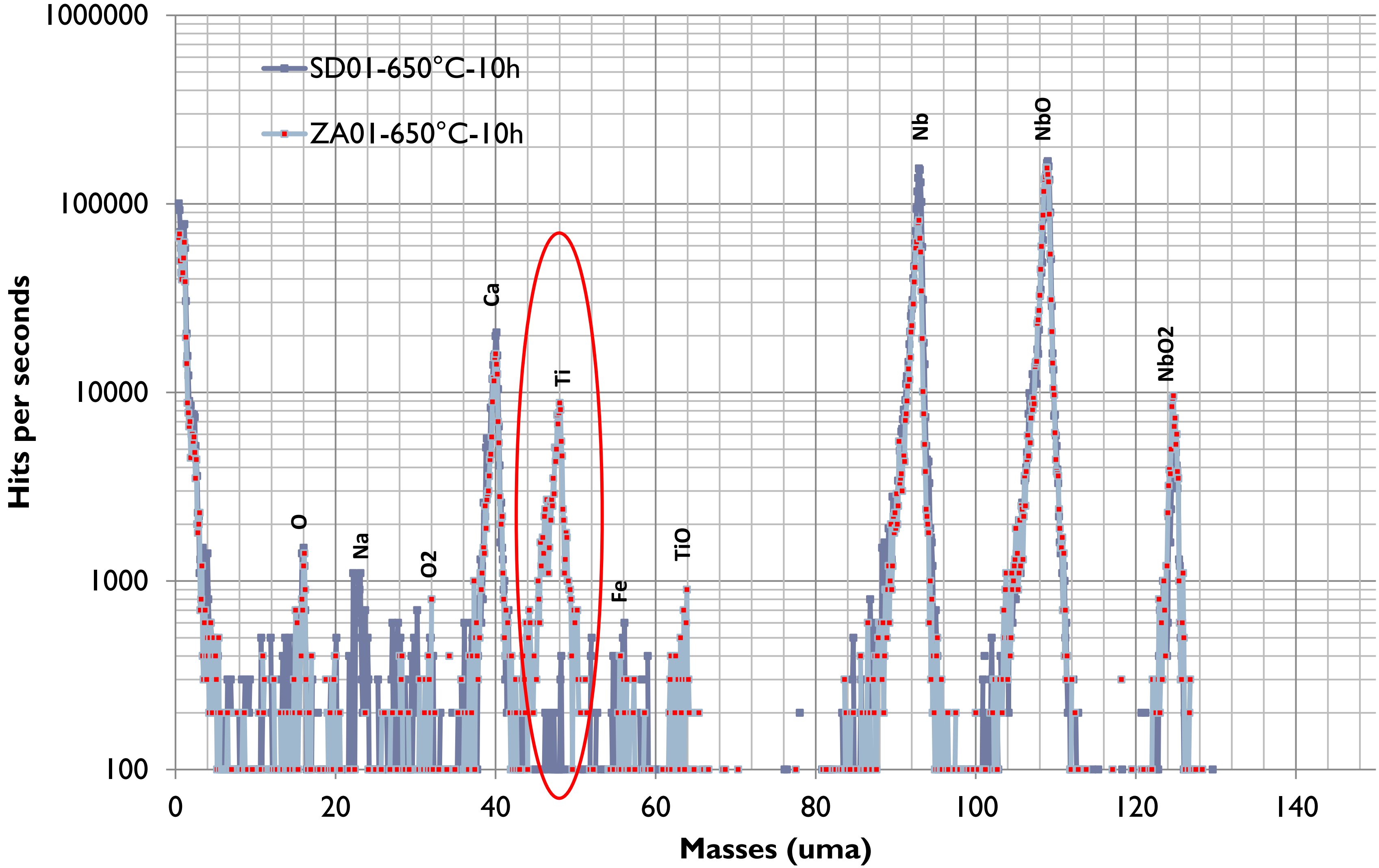


- SIMS (Secondary Ion Mass Spectrometer) analysis to know what is on the surface after heat treatment
  - Compact SIMS from Hiden Analytical

R&D for MYRRHA : MYRTE program

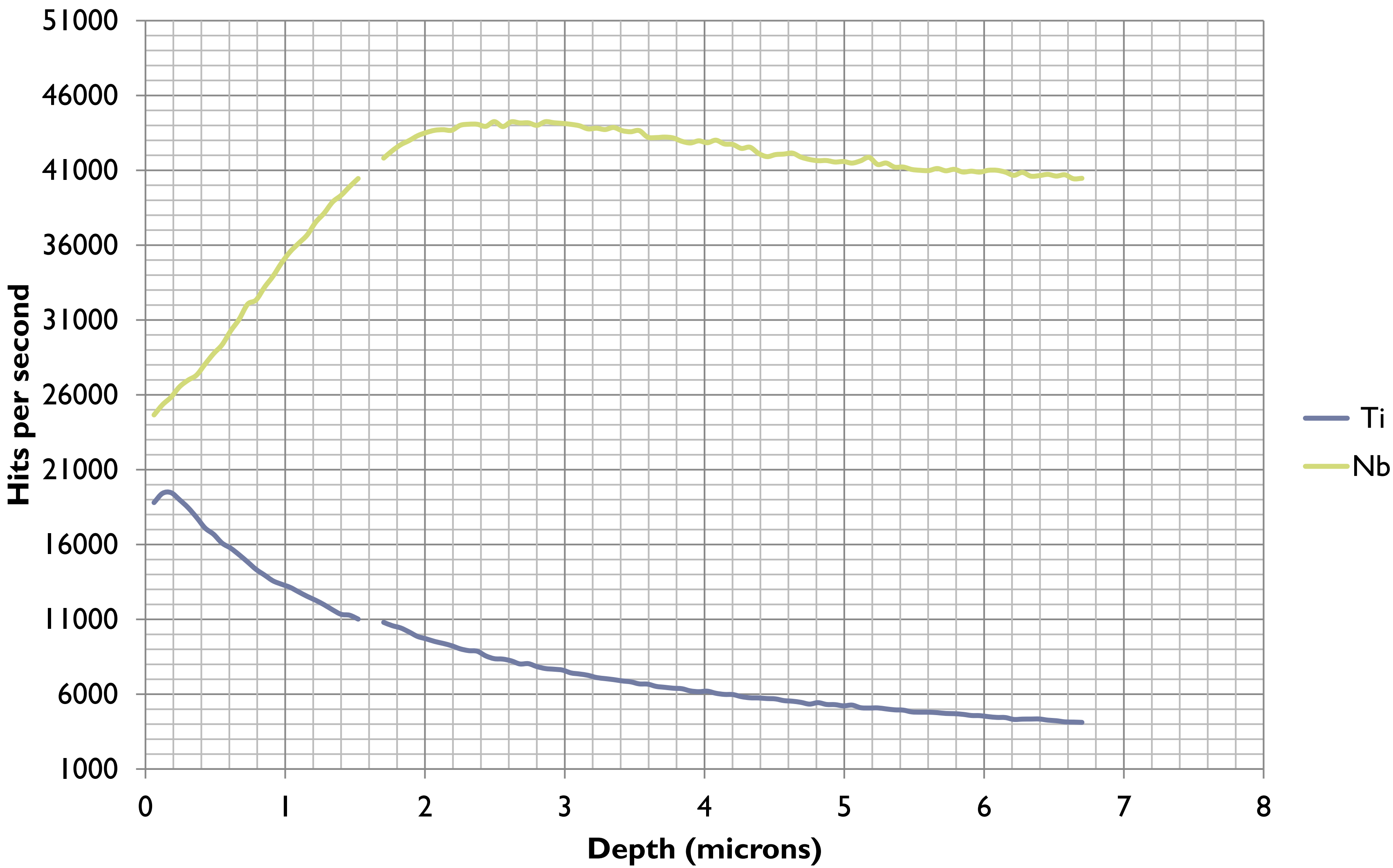
Sample study

- A cavity not shielded during heat treatment :



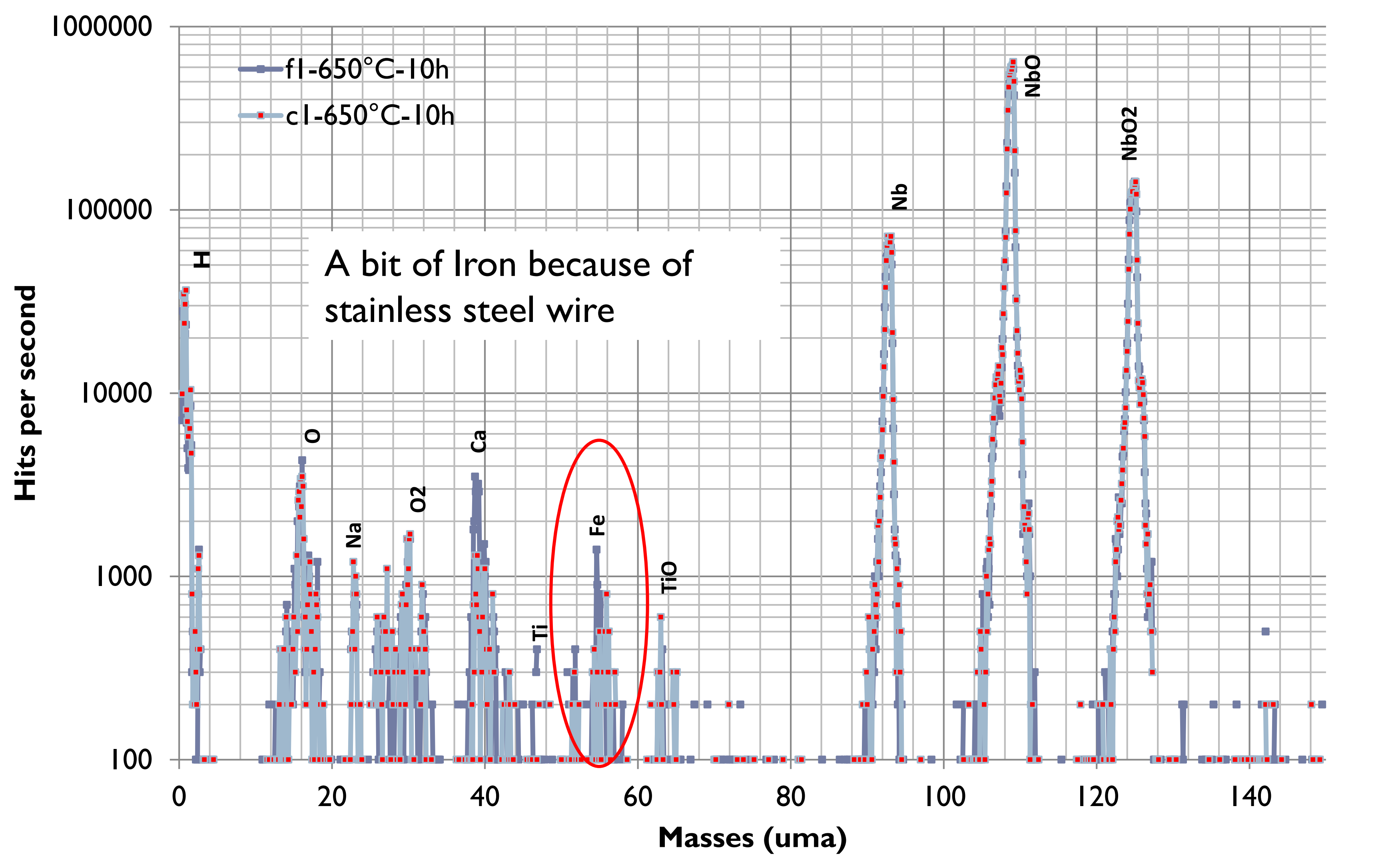
Sample study

- A cavity not shielded during heat treatment :



Sample study

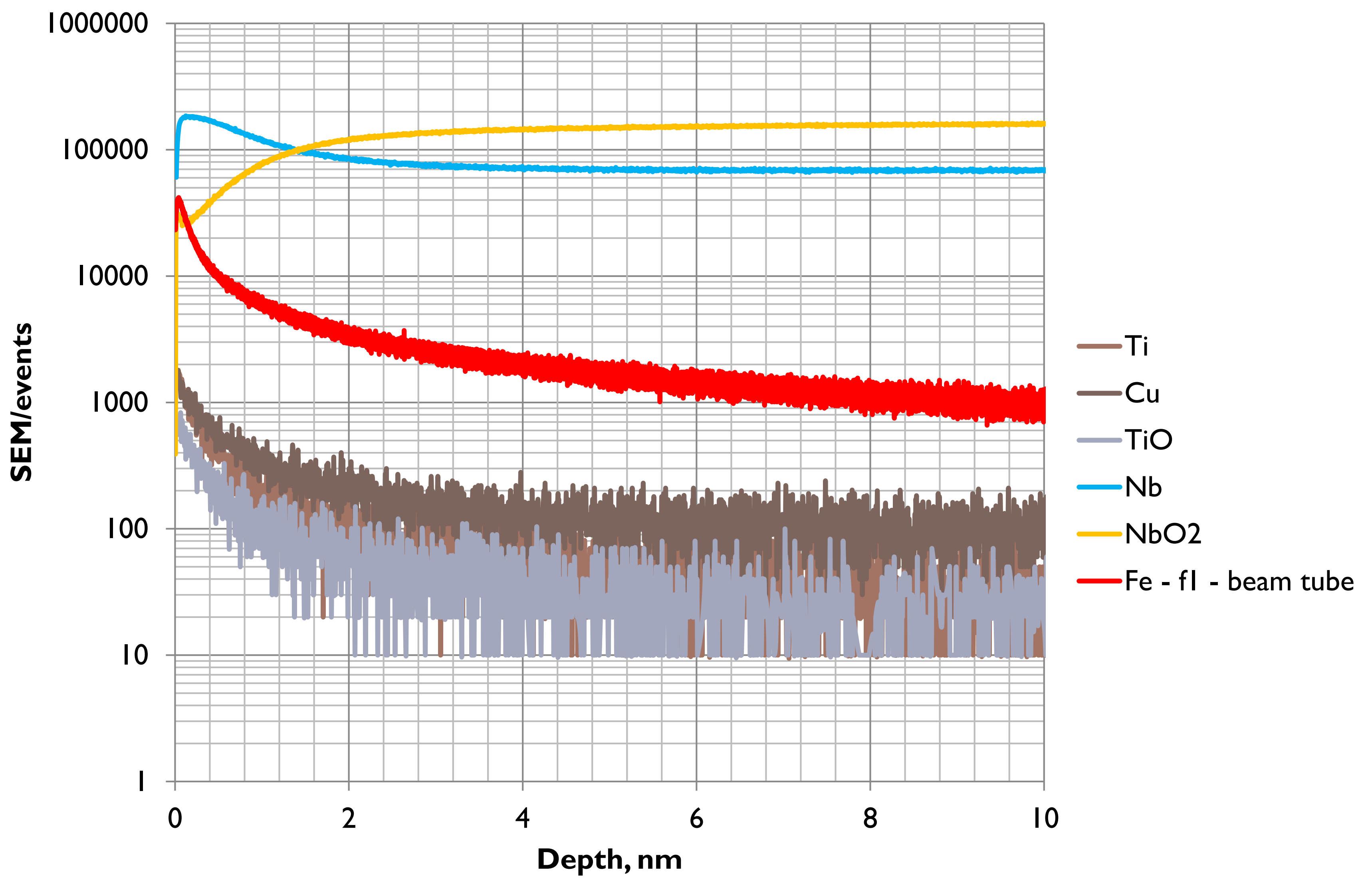
- A cavity shielded during heat treatment :



R&D for MYRRHA : MYRTE program

Sample study

- A cavity shielded during heat treatment :

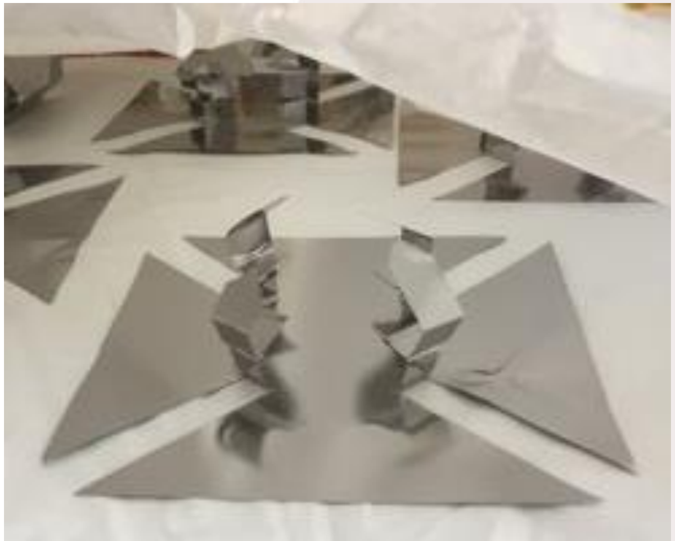


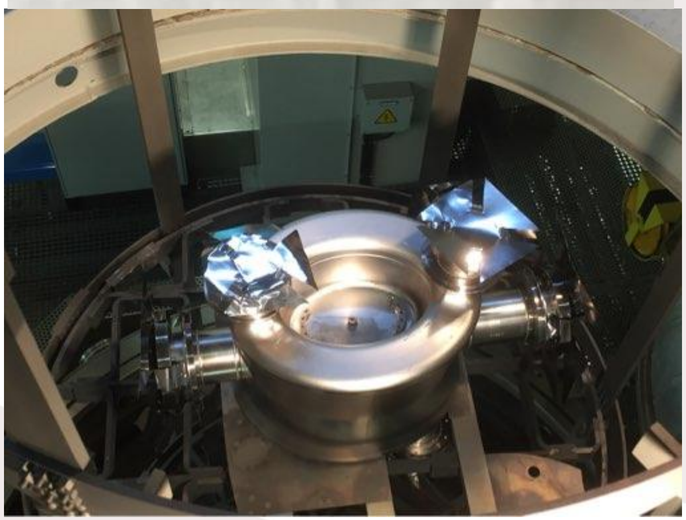
How to compare elliptical and low beta

RF parameters

Cavity type	β	T° (K)	G (Ω)	Qo at 1 nΩ res	F (MHz)	Eacc (MV/m)	Bpk/Eacc (mT/MV/m)
QWR (FRIB)	0.041	2	15	1.4E10	80.5	5.3 (54.6)	10.3
QWR (SPIRAL2)	0.12	4.2	33	8.2E9	88	6.5 (61.7)	9.5
HWR (RISP)	0.12	2	40	3.2E10	162	5.9 (48.4)	8.2
HWR (FRIB)	0.53	2	107	5.3E10	322	7.5 (63)	8.4
SPOKE (ESS)	0.5	2	133	6E10	352	9 (63)	7
Elliptical (ESS)	0.67	2	197	3.4E10	704	16.7 (83.5)	4.8
Elliptical (XFEL)	1	2	271	1.5E10	1300	23.6 (99)	4.2

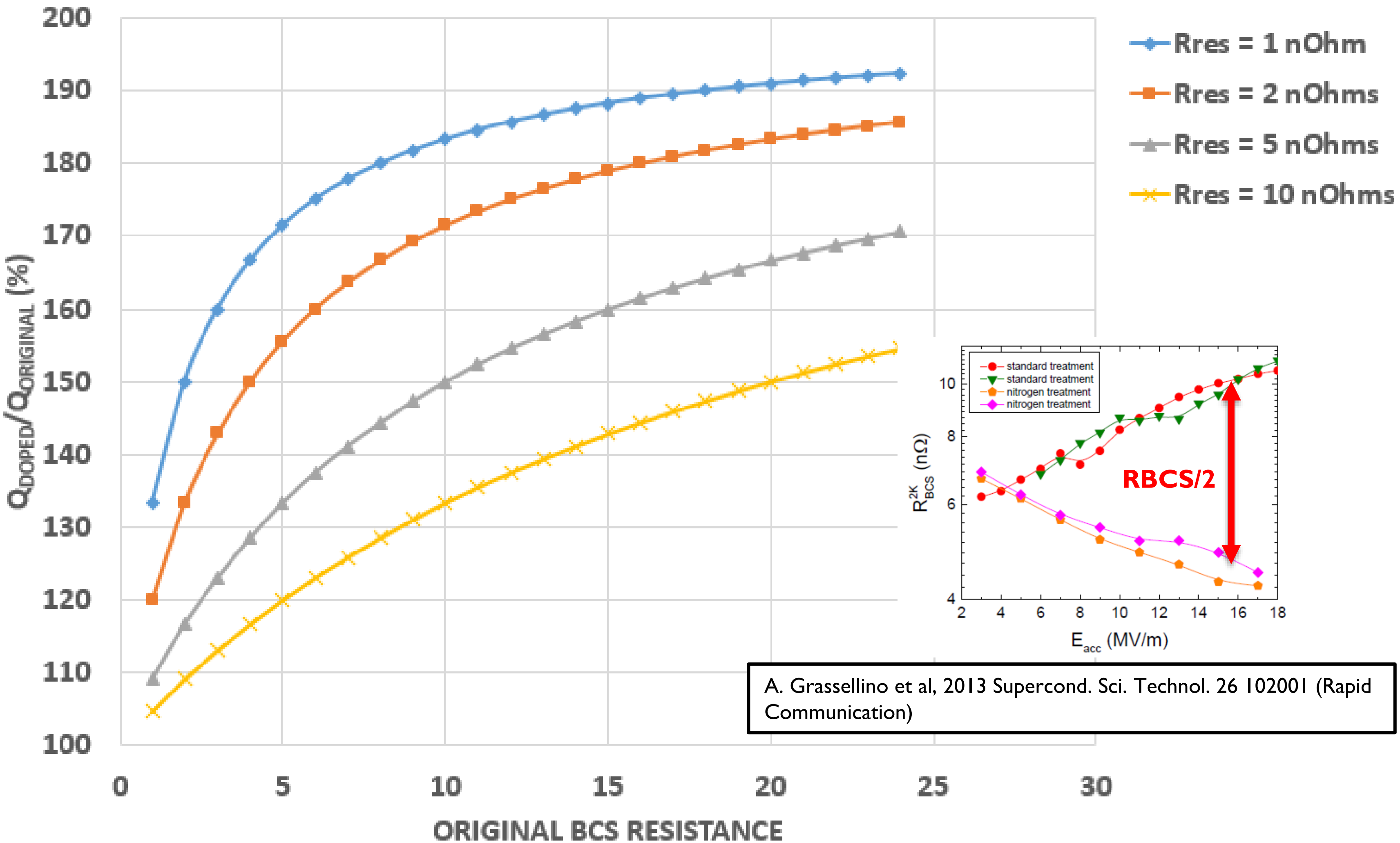
- At CERN





At FERMILAB

IMPROVEMENT OF Q CONSIDERING BCS IS DIVIDED BY 2



A. Grassellino et al, 2013 Supercond. Sci. Technol. 26 102001 (Rapid Communication)