

SEAMLESS QUARTER WAVE RESONATORS FOR HIE ISOLDE

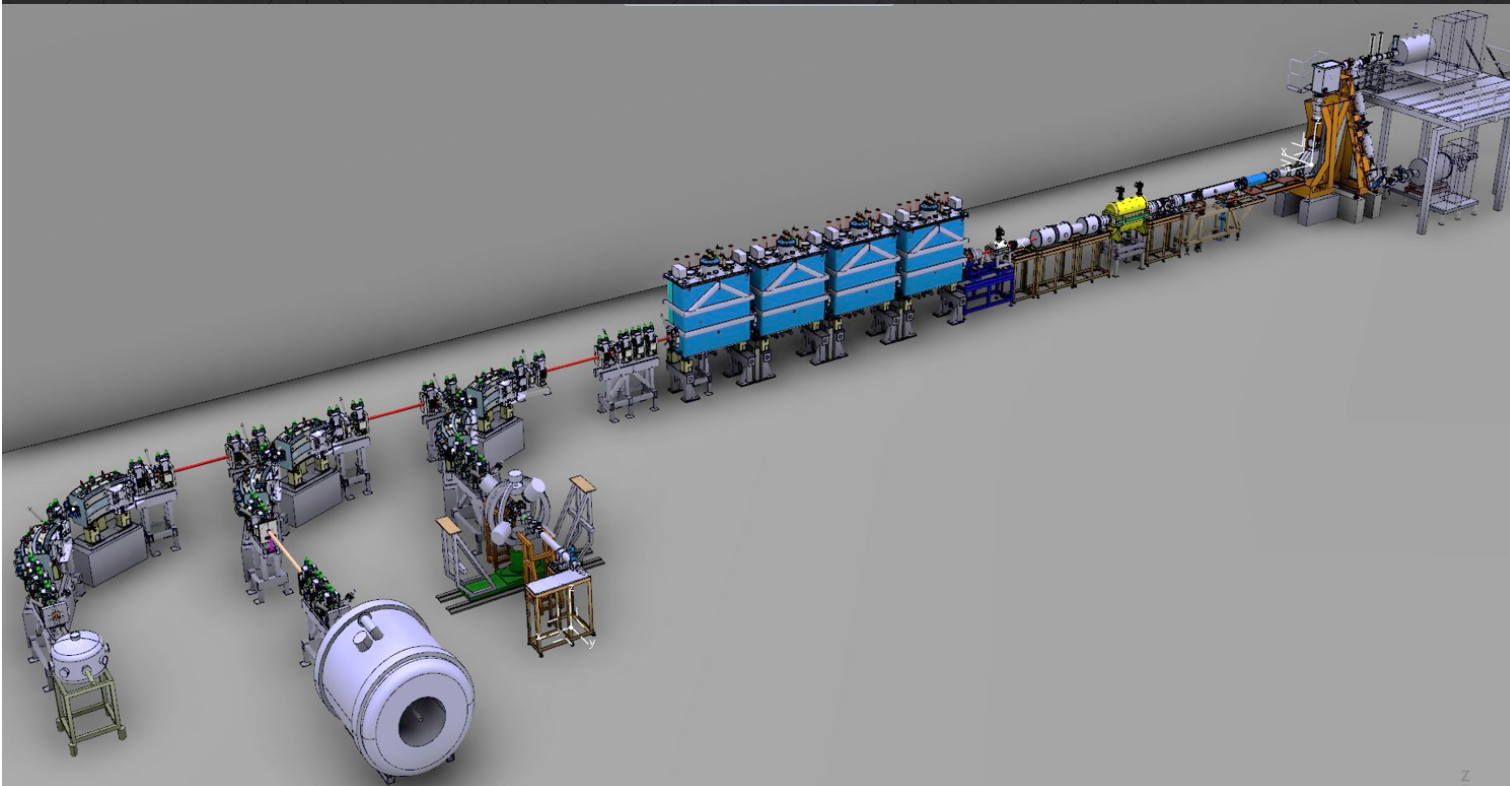
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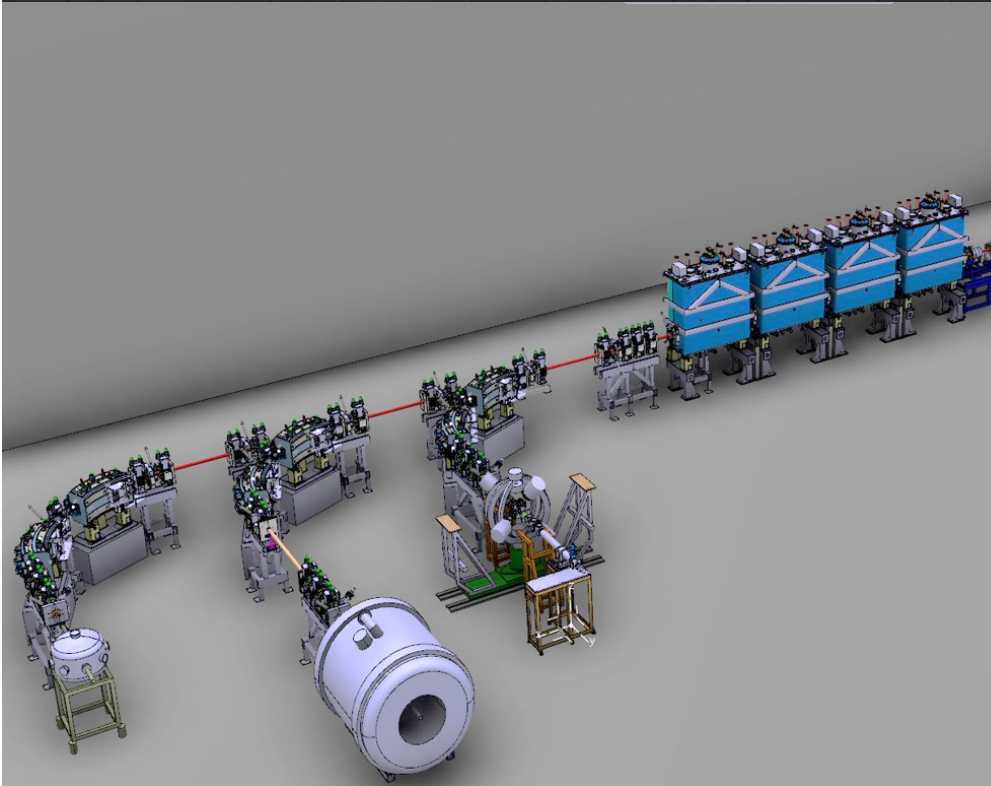
Outline

- ◇ Introduction
 - ◇ Motivation for seamless cavities
 - ◇ Design and manufacturing
 - ◇ Cold test results and analysis
 - ◇ Performance in the HIE ISOLDE linac
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HIE ISOLDE phase II completed

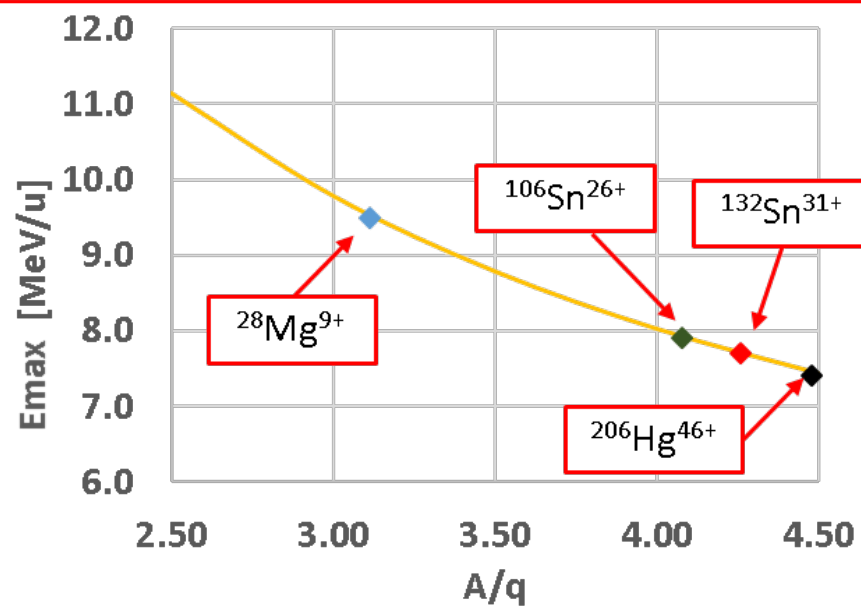


HIE ISOLDE phase II completed



HIE ISOLDE phase II completed

Energy reachable for beams with different A/q during the 2018 campaign



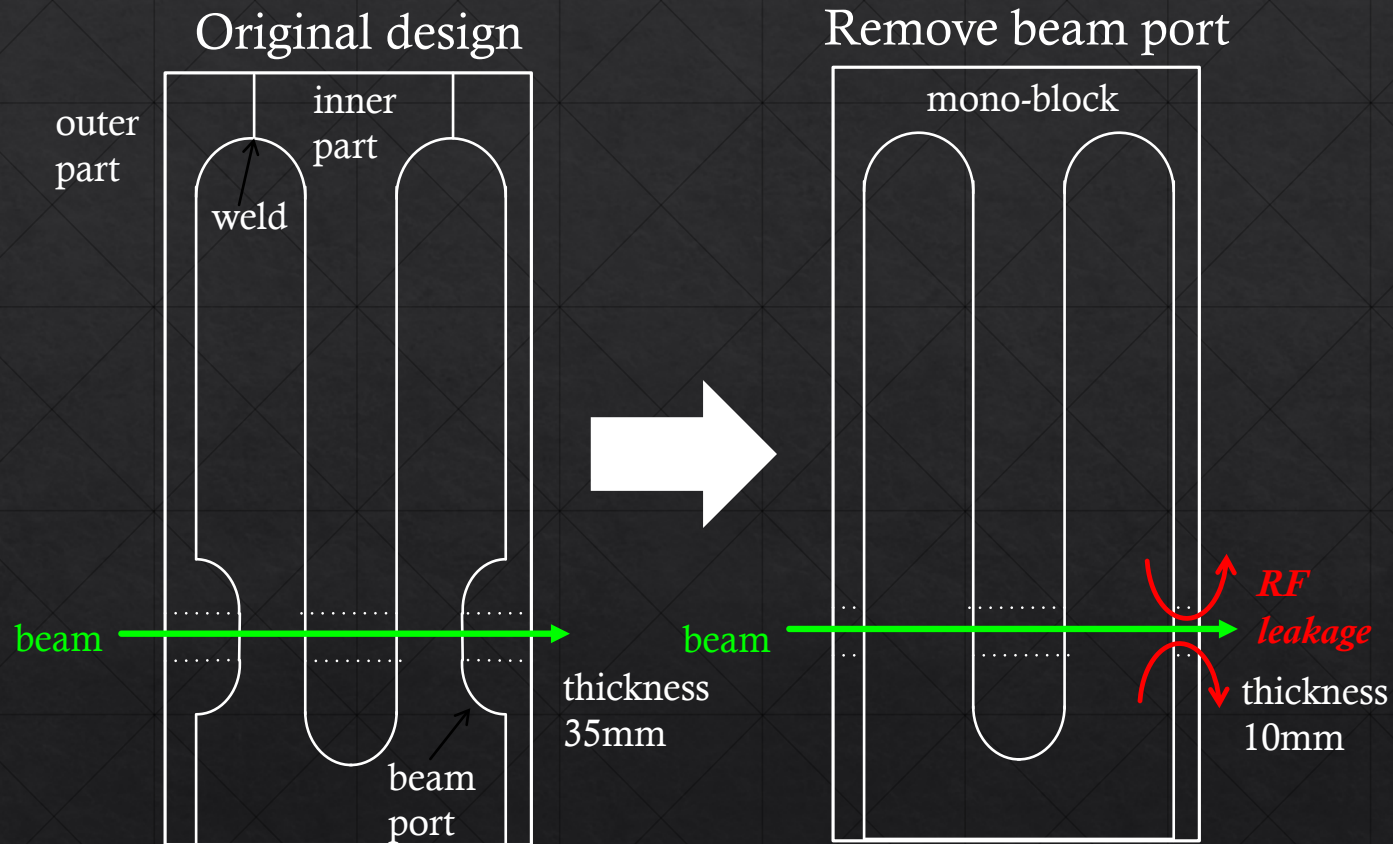
HIE ISOLDE cryomodules with Nb/Cu QWR



Motivation for a seamless design of the copper cavity substrate



Modification for machining from bulk 1/2

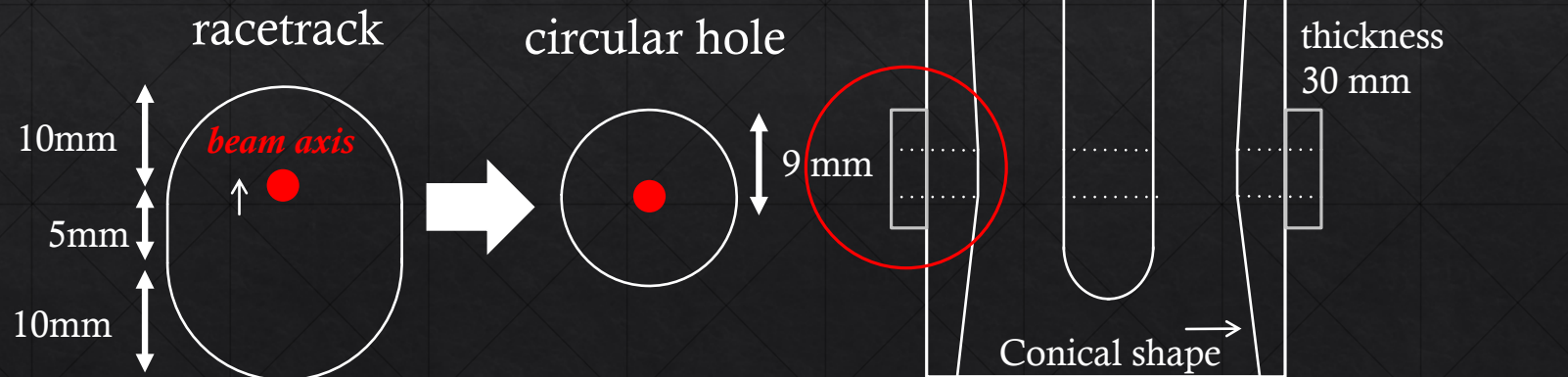


Beam-port nose removal → Important reduction of R/Q , RF leakage

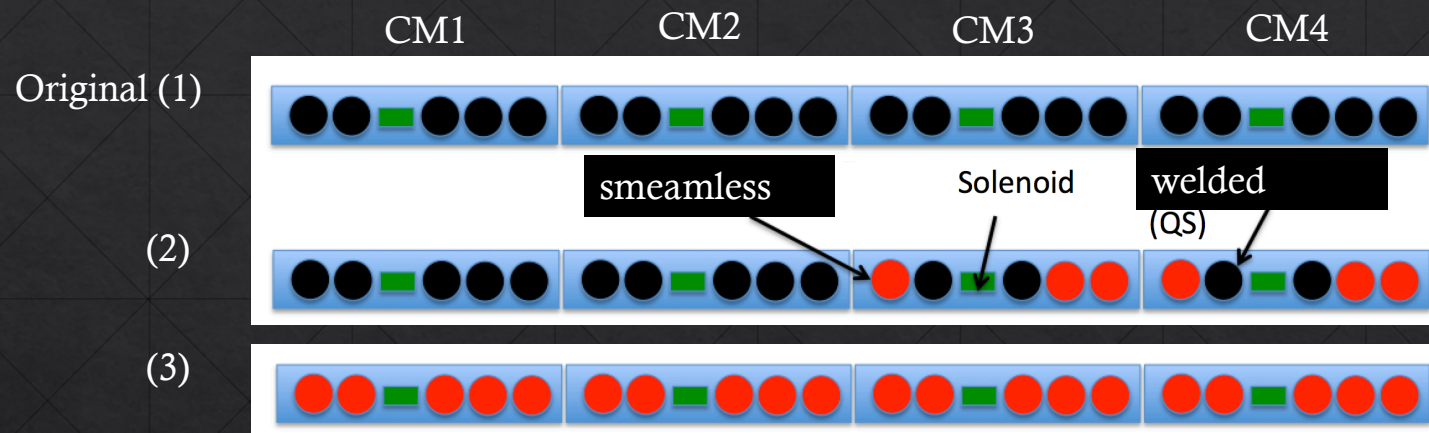
Modification for machining from bulk 2/2

Two ideas to prevent RF leakage

- i) Conical shape of the outer wall + additional external part
→ Partially recover the thickness at the beam hole
- ii) Smaller beam hole



Beam steering correction is not necessary in the last CM



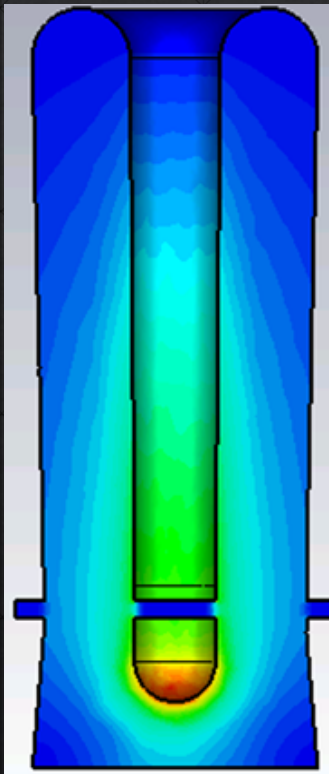
Configuration	Output Energy [MeV/u]	Transmission [%]	Transverse RMS Emittance Growth [%]
Original (1)	14.17	100	0
high β CM (2)	14.2	100	-0.3
All CM (3)	13.86	85	21.2

10

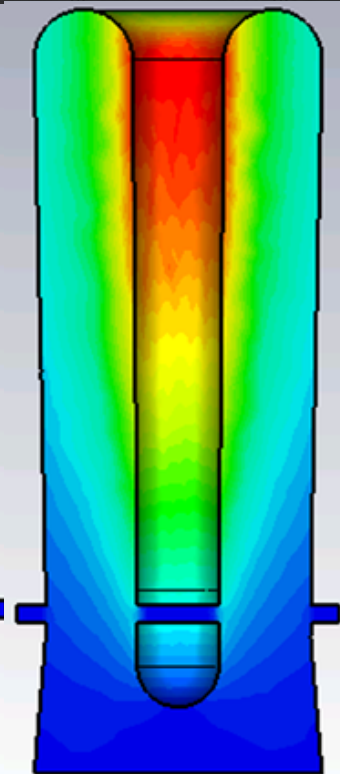
→ Beam steering effects are negligible in the higher- β sections

RF design

E-field

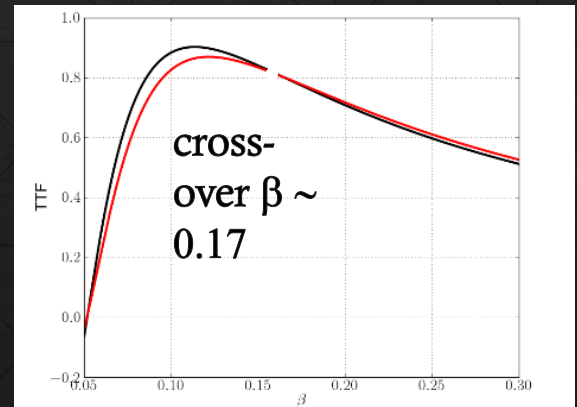
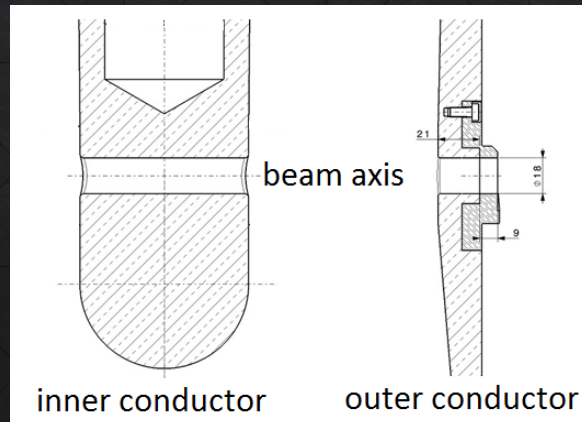
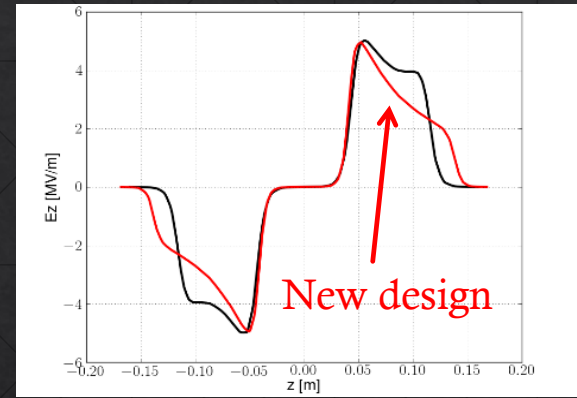


B-field

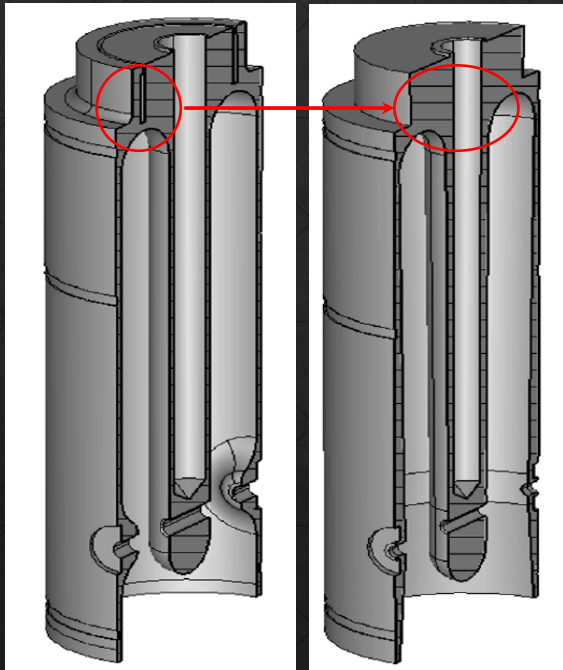


Parameters	QS	QSS
β_{opt} [%]	10.9	12.2
R/Q [Ω]	520	502
$E_{\text{peak}}/E_{\text{acc}}$	5.4	5.2
$B_{\text{peak}}/E_{\text{acc}}$ [Gauss/(MV/m)]	96	93
$G = R_s \cdot Q$ [Ω]	30.34	30.71
U/E_{acc}^2 [J/(MV/m) ²]	0.207	0.214
P_c at 6 MV/m [W]*	7.7	7.9

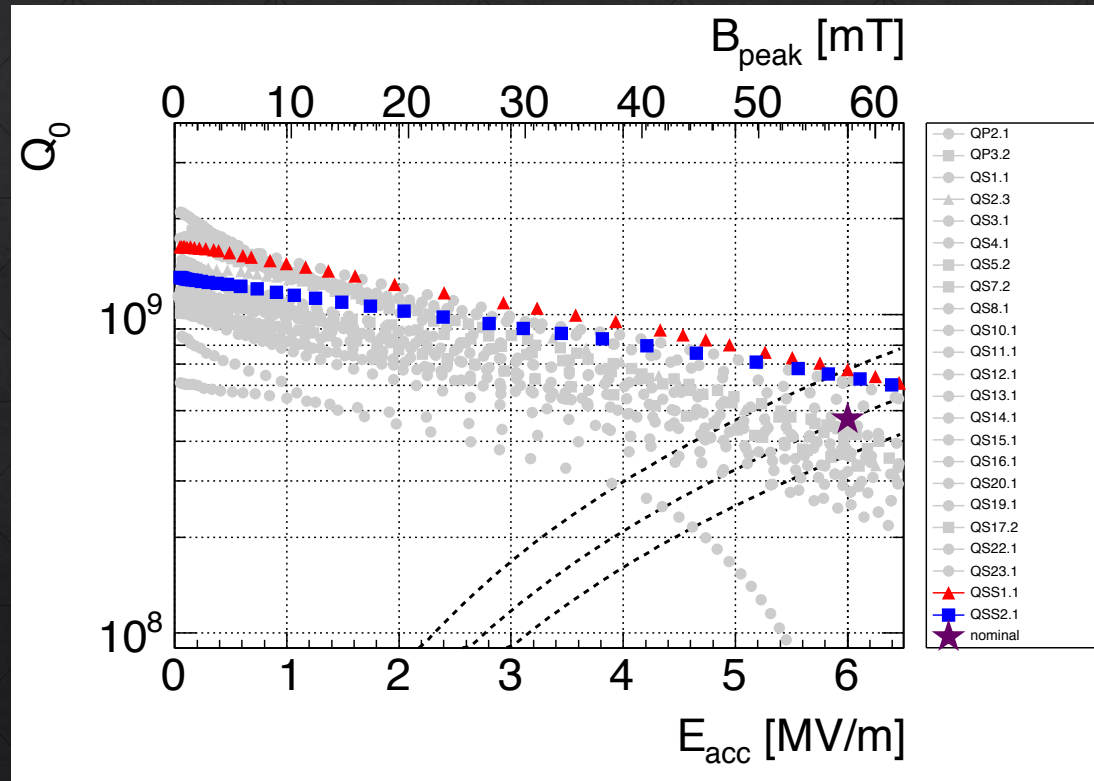
* calculated assuming $R_s = 50 \text{ n}\Omega$



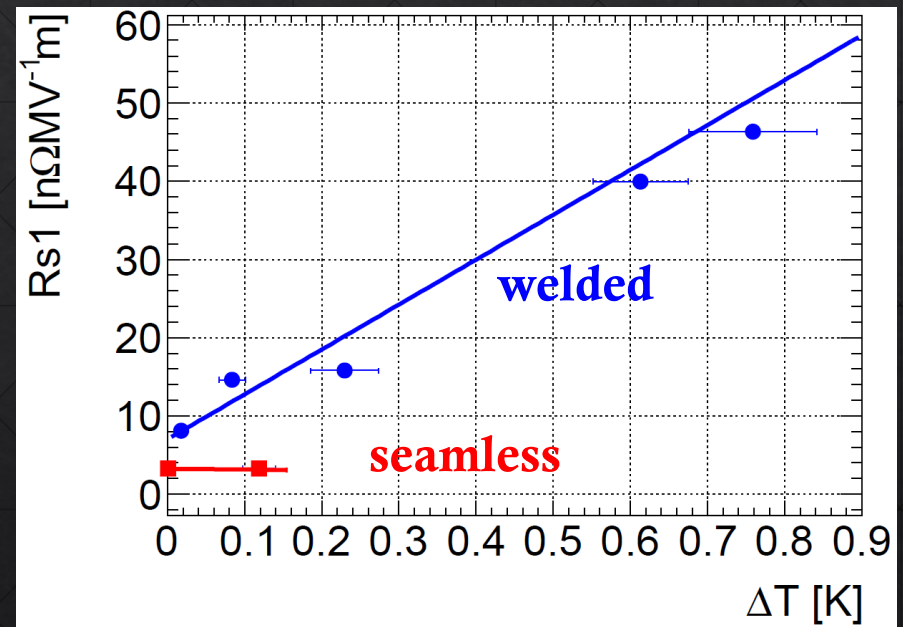
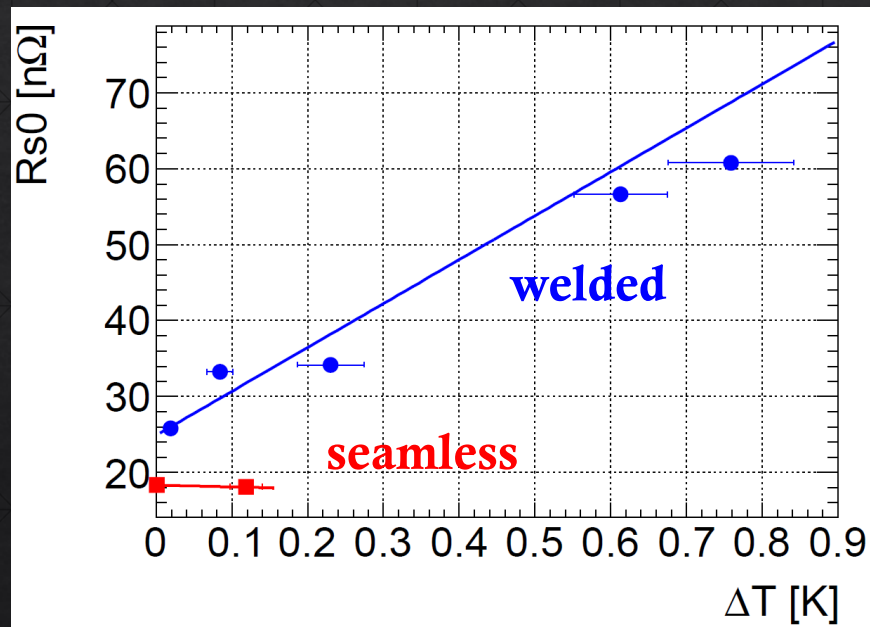
Mechanical design and manufacturing



Performances of seamless cavities in vertical tests as compared to the welded design series production

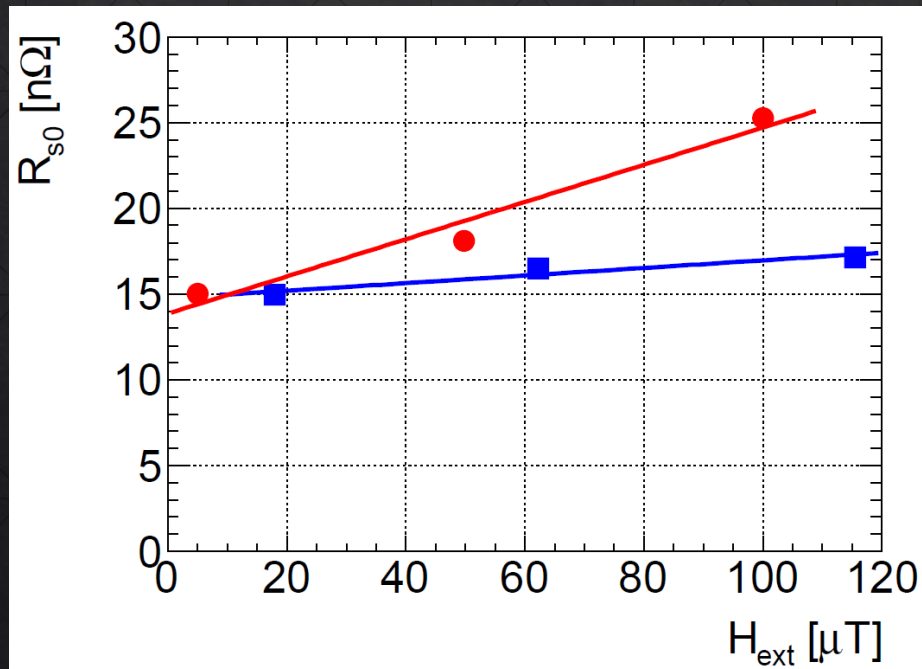


Sensitivity to thermal gradient at T_c crossing

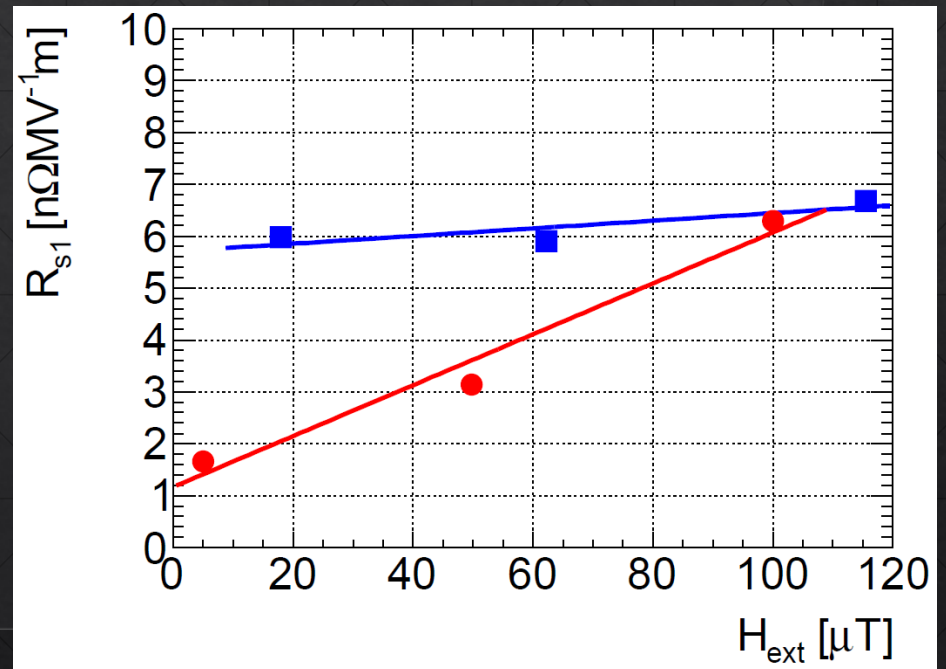


Sensitivity to trapped flux at T_c crossing

Surface resistance at zero RF field vs trapped field



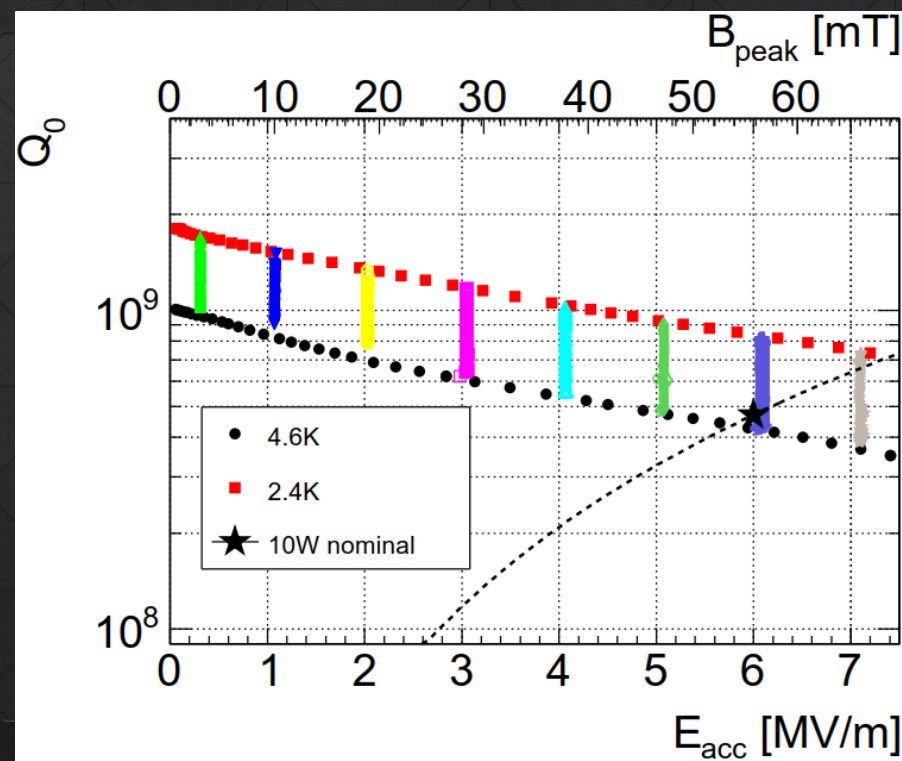
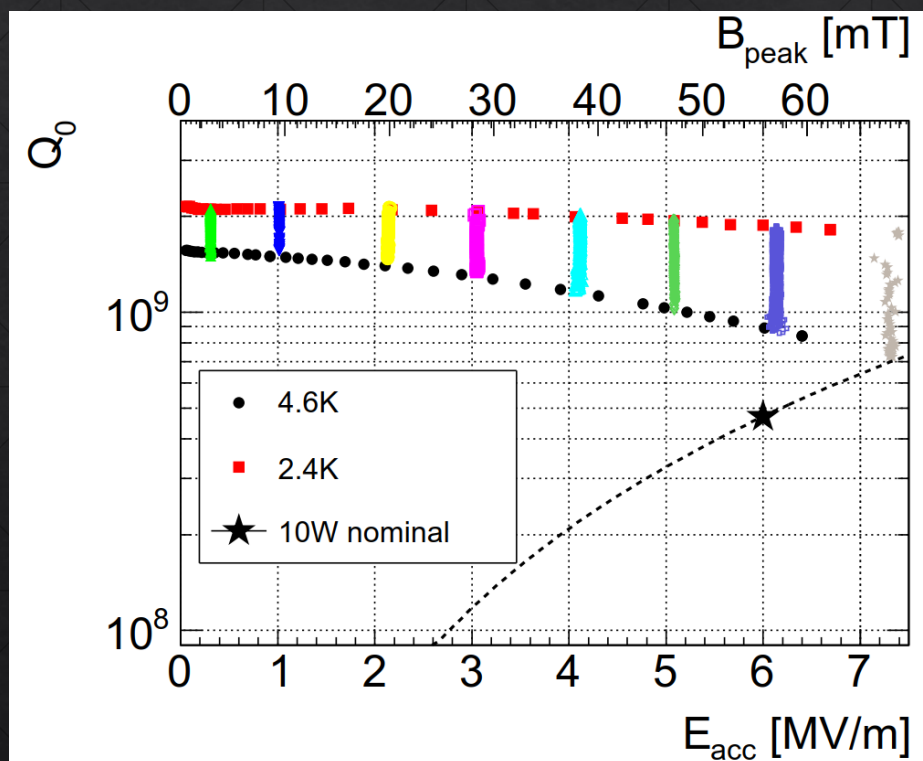
Surface resistance slope vs trapped field



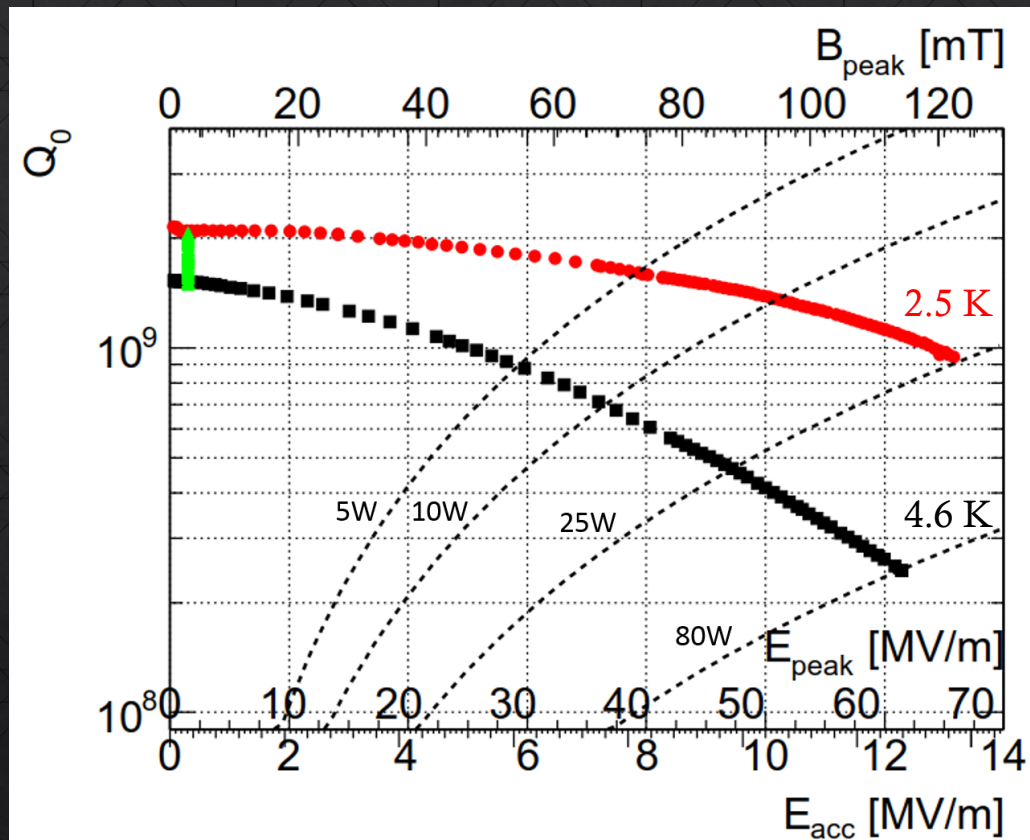
Systematic study of R_s vs T , H_{rf} , B_{ext} .

B-field compensated when cavity crossed T_c

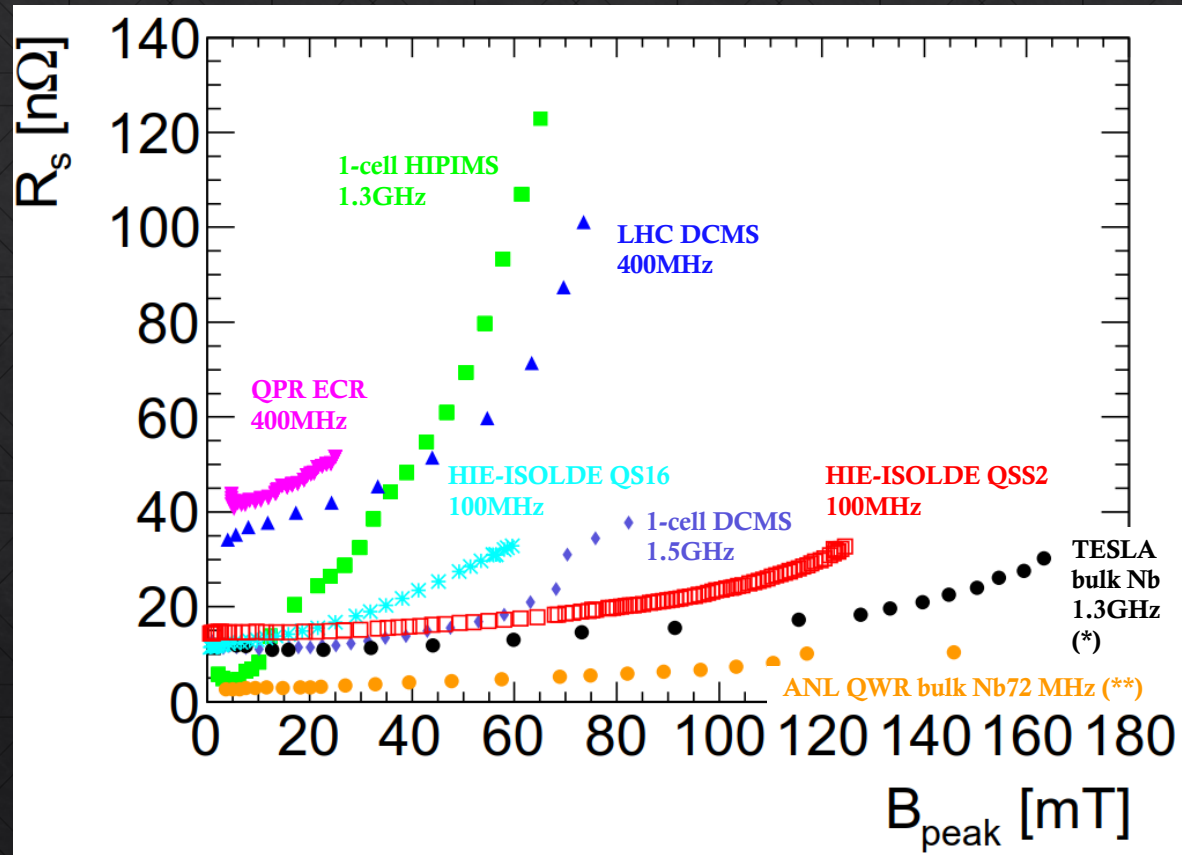
B-field enhanced when cavity crossed T_c



QSS2 performances (cooled in $\sim 5 \mu\text{T}$ ambient field)

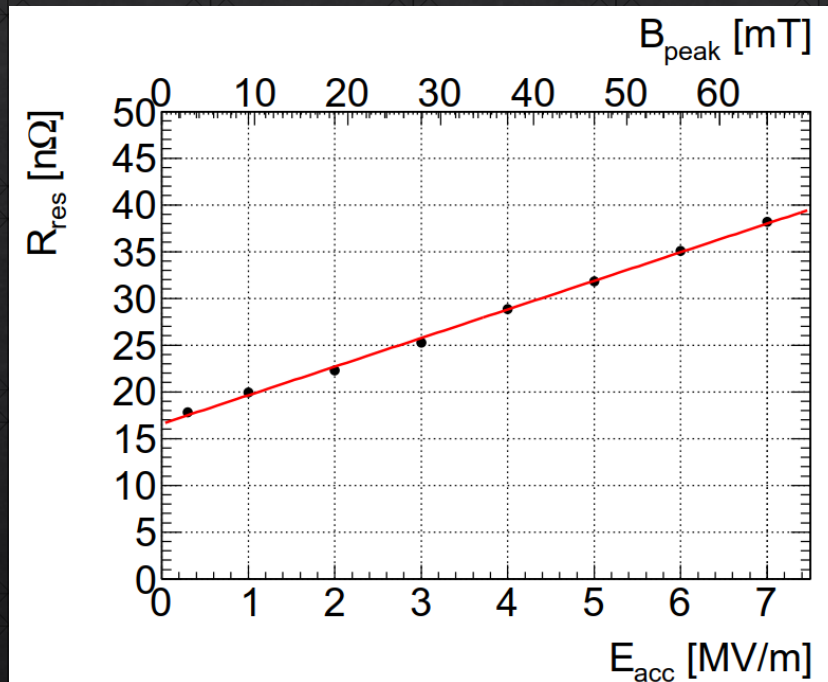


Rs (B, ~2K) of Nb/Cu cavities compared to bulk Nb

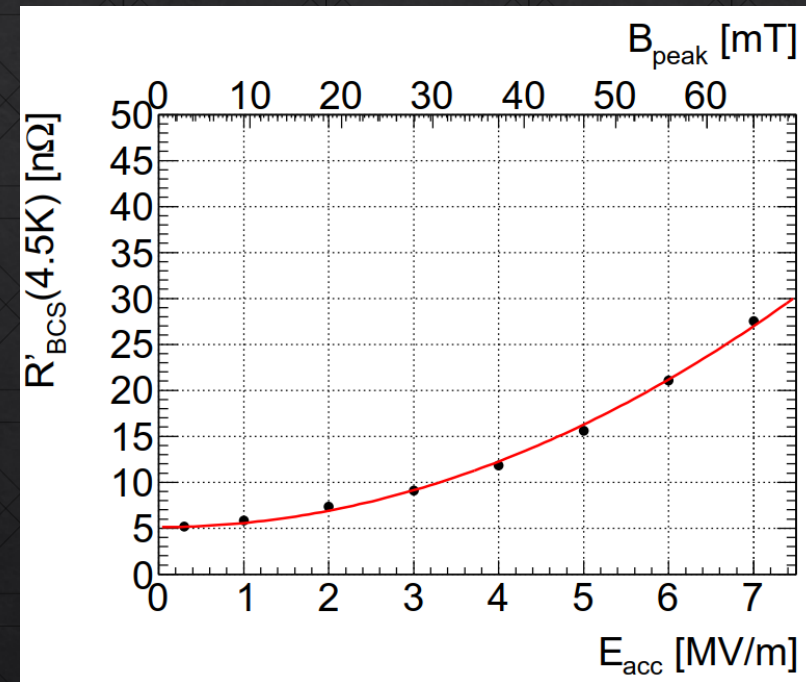


Decomposition of Q slopes

B-field enhanced when cavity crossed T_c



B-field compensated when cavity crossed T_c

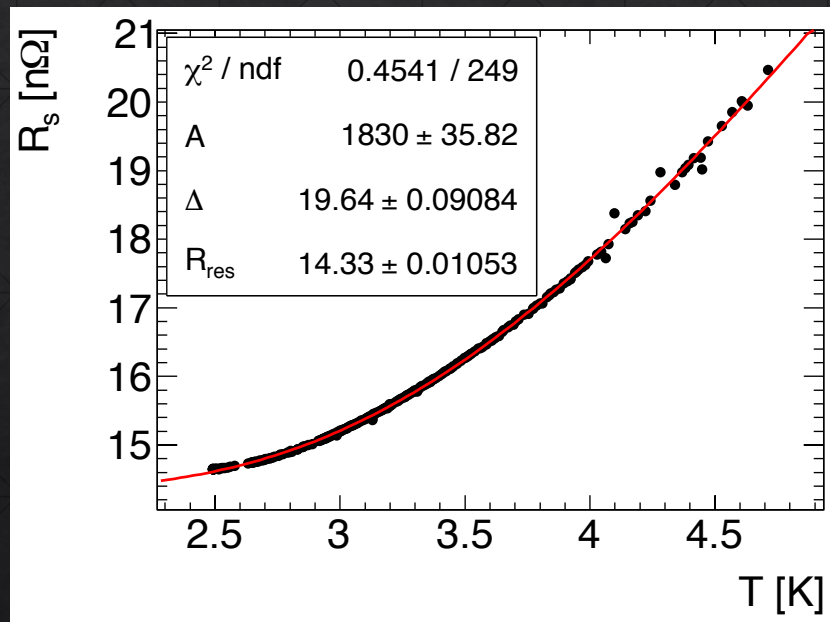


1. Linearly RF dependent Q-slope in residual resistance caused by trapped flux
2. Exponentially RF dependent Q-slope in BCS-like resistance (exponentially T dependent)

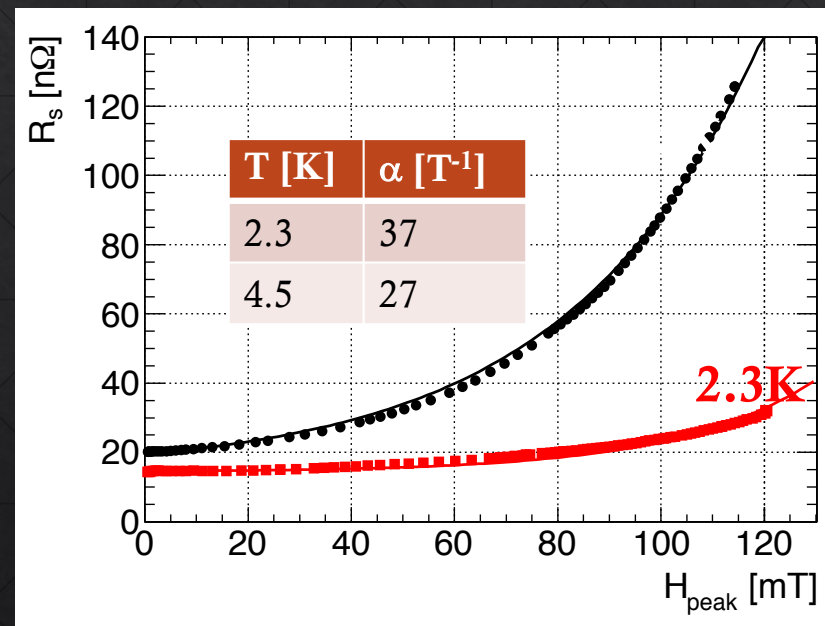
An empirically found formula to fit the non-linear Q-slope

$$R_s(T, B) = \frac{A}{T} \exp\left(-\frac{\Delta}{k_B T} + \alpha B\right) + R_{res} + R_{fl} B$$

(A, Δ, R_{res}) from R_s vs T data



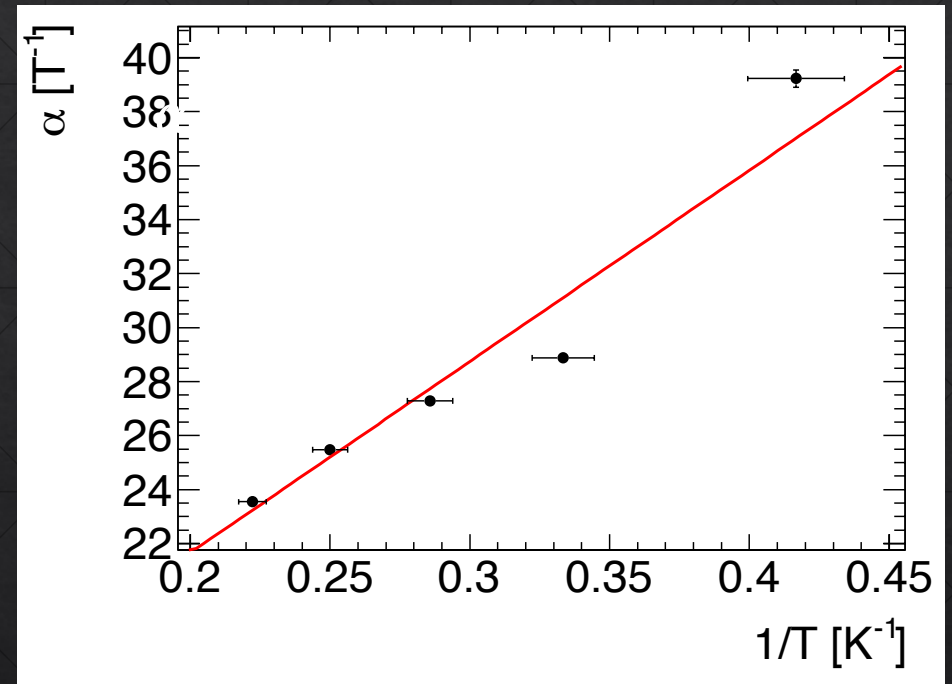
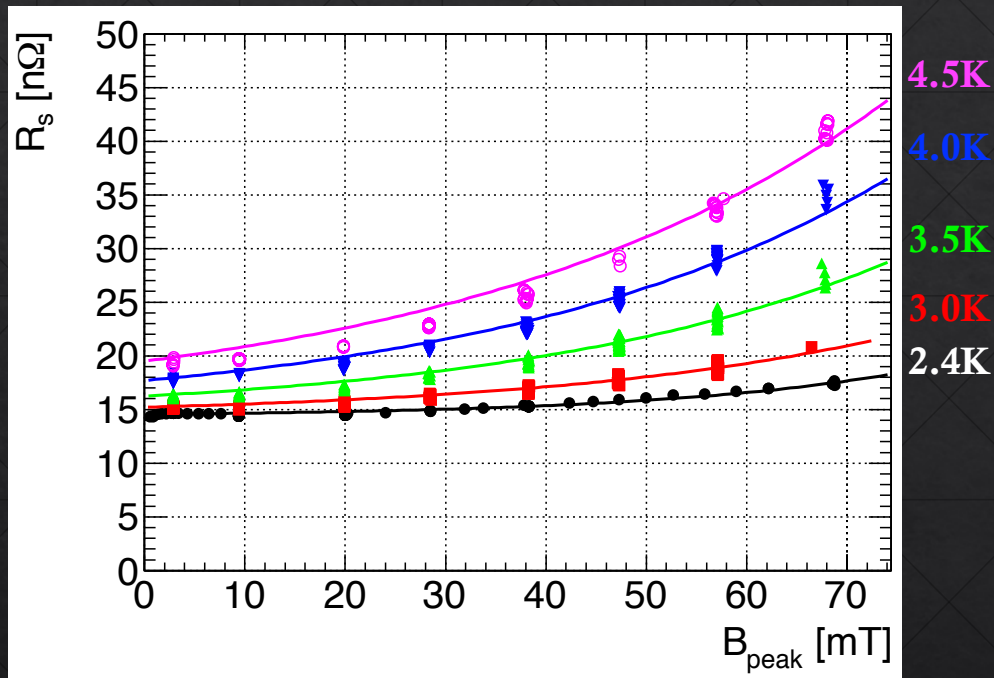
Fit R_s vs H and determine α



Such an exponential dependence has been reported by others (bulk Nb and Nb/Cu)

1. R. L. Geng (Cornell) "Thermal analysis of a 200MHz Nb/Cu cavity" SRF2001
2. D. Longuevergne (IPNO) "Magnetic dependence of the energy gap:..." SRF2013

Temperature dependence of α (B_{ext} -compensated)

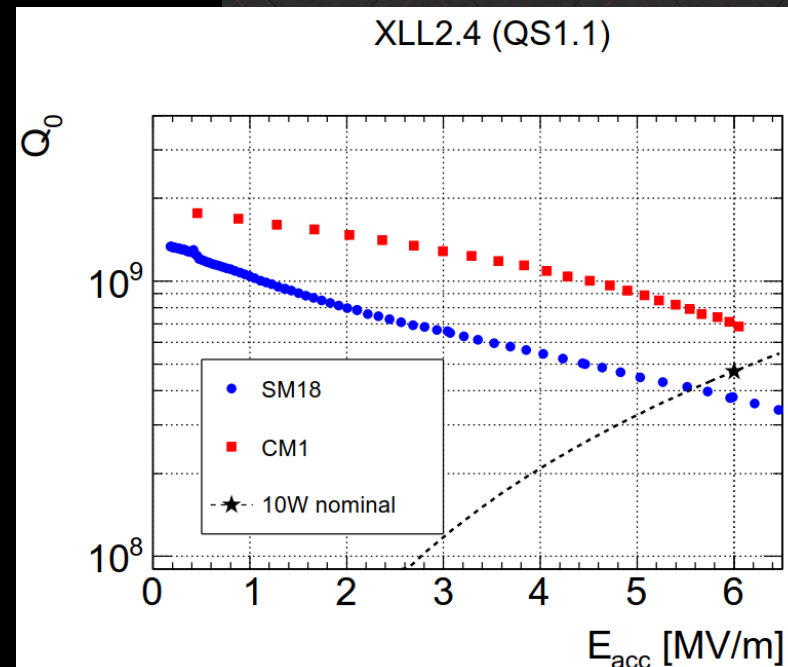
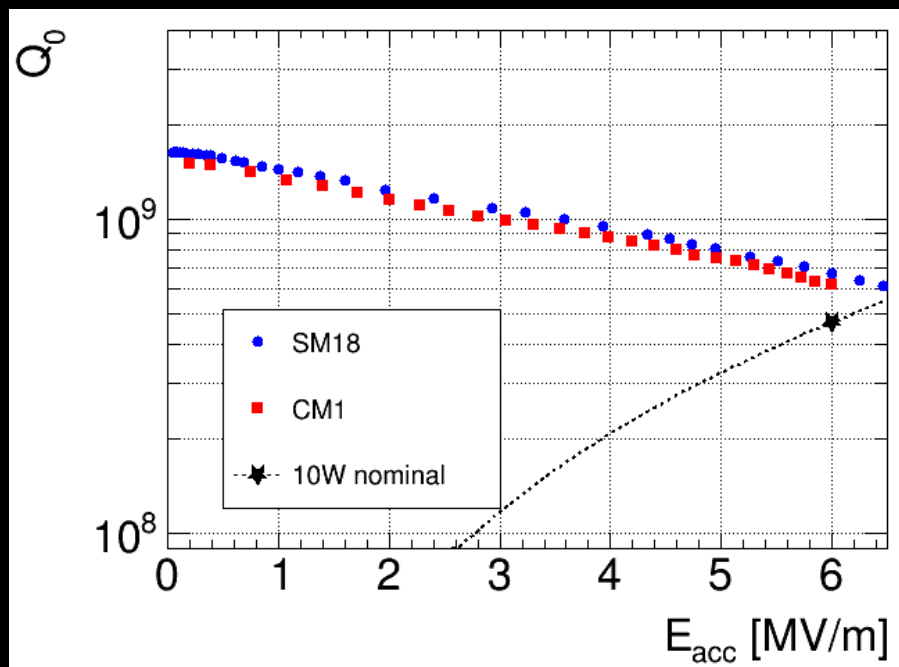


$\alpha \propto T^{-1}$ from the data $\rightarrow$ change the parameter by $\alpha = M/k_B T$

$$R_s(T, B) = \frac{A}{T} \exp\left(-\frac{\Delta}{k_B T} + \frac{MB}{k_B T}\right) + R_{\text{res}} \rightarrow R_s(T, B) = \frac{A}{T} \exp\left(-\frac{\Delta - MB}{k_B T}\right) + R_{\text{res}}$$

This new constant M has a dimension of magnetic moment [JT⁻¹]

Vertical test vs performance in the linac

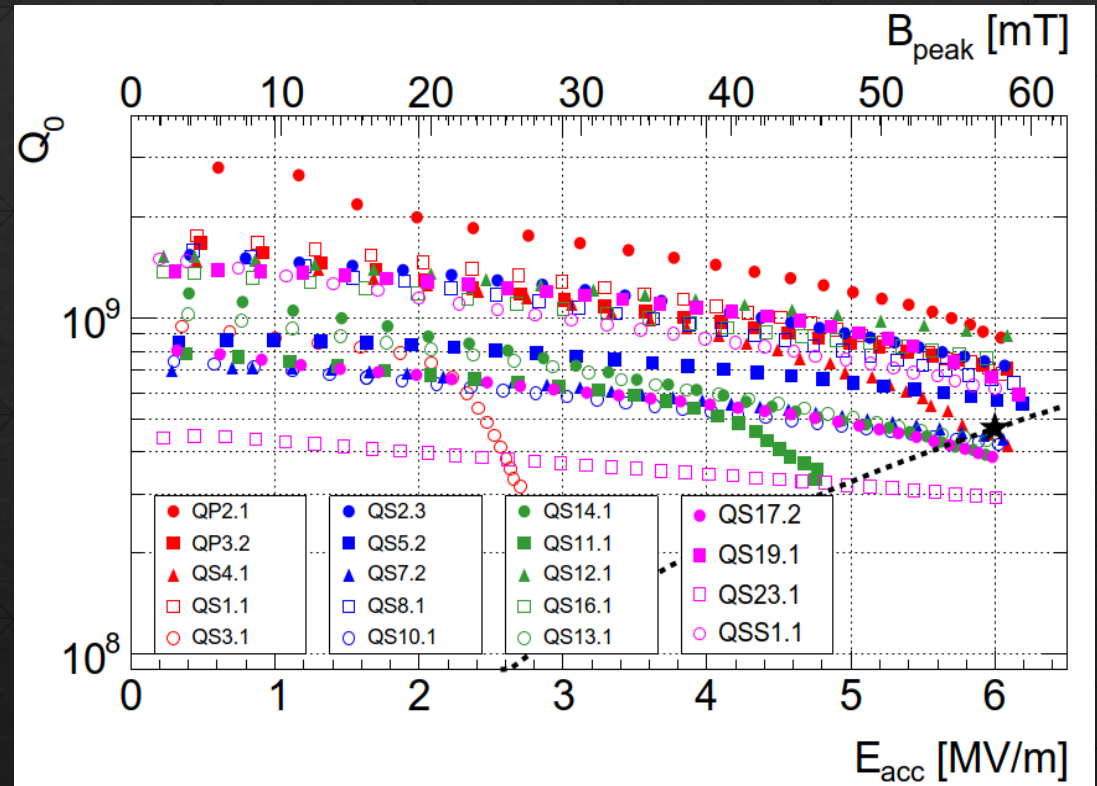


QSS results are consistent with each other within 10% (typical calibration error)

- The ambient magnetic field in the cryomodule is similar to the one in the vertical test stand
- The welded cavity's performance is improved by more uniform cooling down in cryomodule

HIE ISOLDE cavity performances (vertical tests vs linac)

Cavity	VT	L2015	L2016	L2017	L2018
QP2.1	6.3	8.2	3.5MV/m	11.0	8.7
QP3.2	4.3	5.4	7.9	7.7	7.3
QS4.1	4.3	5.9	6.6	7.1	4.4
QS1.1	3.7	6.6	7.1	7.9	6.9
QS3.1	3.6	4.4	4.5MV/m	4.5MV/m	2MV/m
QS2.3	3.6	-	6.4	8.4	7.4
QS5.2	3.5	-	4.2	6.2	5.7
QS7.2	4.0	-	4.3	5.3	4.4
QS8.1	3.7	-	4.9	7.2	6.5
QS10.1	3.1	-	4.0	5.7	4.2
QS14.1	2.4	-	-	4.1	3.9
QS11.1	2.8	-	-	3.5MV/m	4MV/m
QS12.1	3.0	-	-	9.0	9.0
QS16.1	5.3	-	-	9.4	7.6
QS13.1	2.8	-	-	4.1	4.3
QS17.2	4.3	-	-	-	3.9
QS19.1	4.6	-	-	-	6.6
QS22.2	3.7	-	-	-	-
QS23.1	3.2	-	-	-	2.9
QSS1.1	6.7	-	-	-	6.2



$Q_0/10^8$ values at 6 MV/m (onset of field emission is given if gradient was limited)

Summary

- ◇ Seamless QWRs for HIE-ISOLDE designed, coated and tested at CERN
 - ◇ Cavity substrates obtained in industry by machining single OFE copper billets
 - ◇ The RF performances of these cavities were the best of the whole series production in the acceptance tests in a vertical cryostat.
 - ◇ One cavity was extensively studied in various conditions of shielding, and showed unprecedented peak fields for the Nb/Cu technology.
 - ◇ Peculiar features of the seamless cavities are the higher sensitivity to magnetic flux trapping, and the lack of sensitivity to the cool down conditions.
 - ◇ This technique, while removing at the source the risk of defects around the electron beam welds, is also **cost effective** and provides a much better cooling of the resonator.
 - ◇ The validation of the QSS design was complete in summer 2018, with the first ion beam acceleration.
 - ◇ Since then, the first seamless cavity is operating and delivering accelerated beam to the users
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