FACED ISSUES IN REA3 QUARTER-WAVE RESONATORS AND THEIR SUCCESSFUL RESOLUTION

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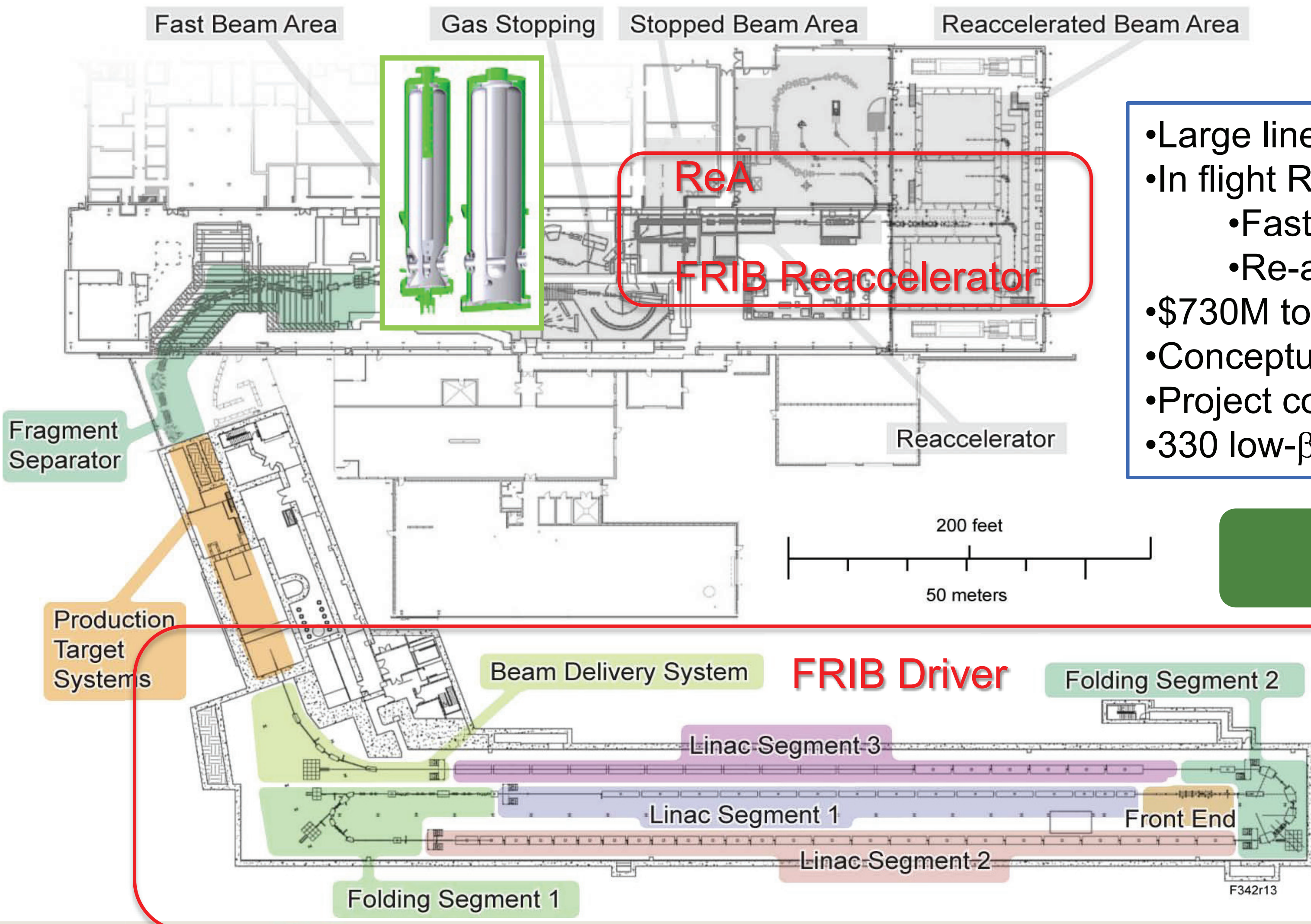
Michigan State University designs and establishes FRIB as a DOE Office of Science National User Facility in support of the mission of the Office of Nuclear Physics.

Facility for Rare Ion Beams

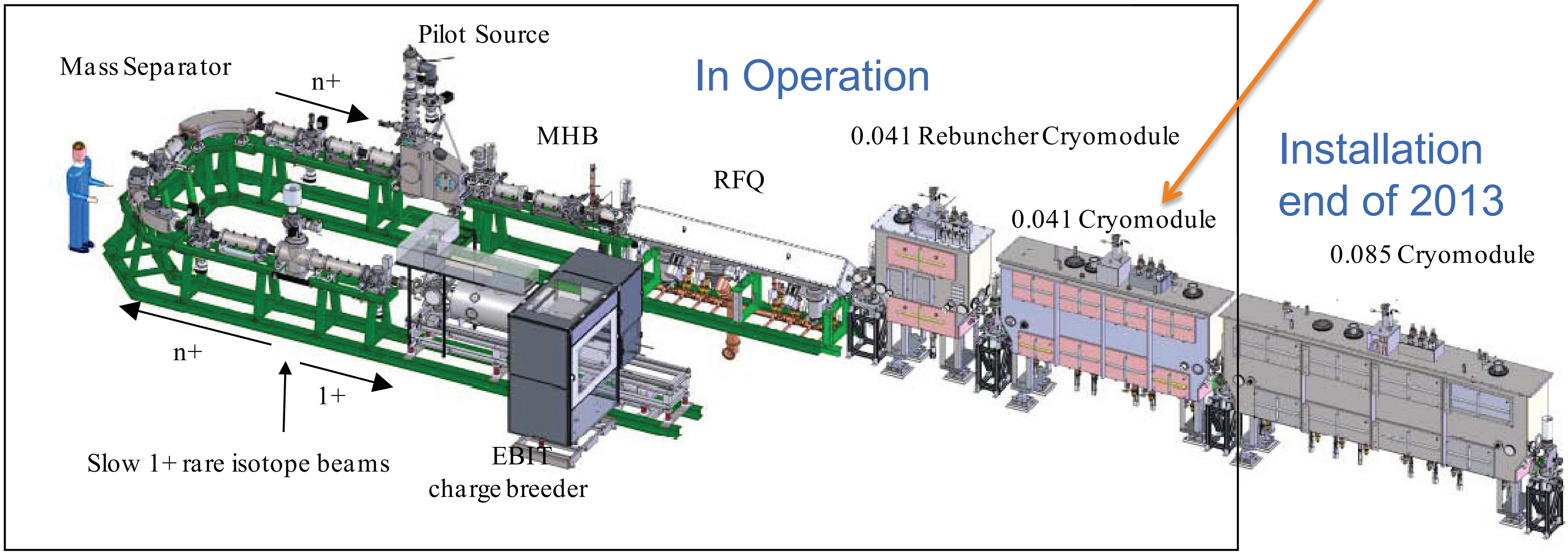


- Large linear RIB facility
- In flight RIB production
  - Fast RIBs
  - Re-accelerated RIBs
- $730M total cost
- Conceptual Design in 2010
- Project completion in 2020
- 330 low-β SC resonators

M. Leitner
MOIOA01

ReA3 Re-accelerator Linac

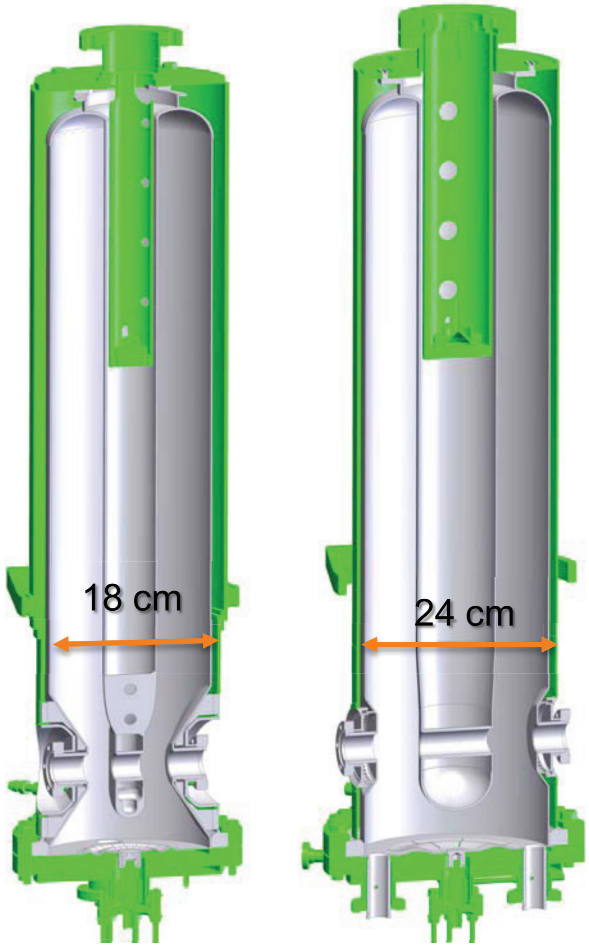
- First SRF linac at MSU, β=0.041 QWRs in operation since 2 years
- Excellent test bench for FRIB QWRs
- Operation T=4.5K



Original ReA3 Cavity Design Characteristics

- Main characteristics
  - Coaxial structure
  - Inner conductor with spherical end cup and mechanical damper
  - Semi-toroidal shorting plate
  - Beam ports deep drawn in the outer conductor
  - Tuning by deformation of the central (slotted) section of the bottom plate
  - Very large tuning range obtained by putting the tuning plate very close to the inner conductor
  - Helium vessel in Nb, tig-welded in air with Ar gas flow
  - RF ports located in the removable bottom plate
- Goal: high performance, moderate cost
- Prototypes for the FRIB driver QWRs

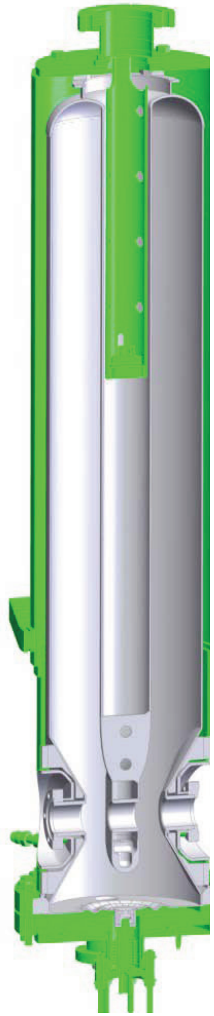
β=0.041 β=0.085



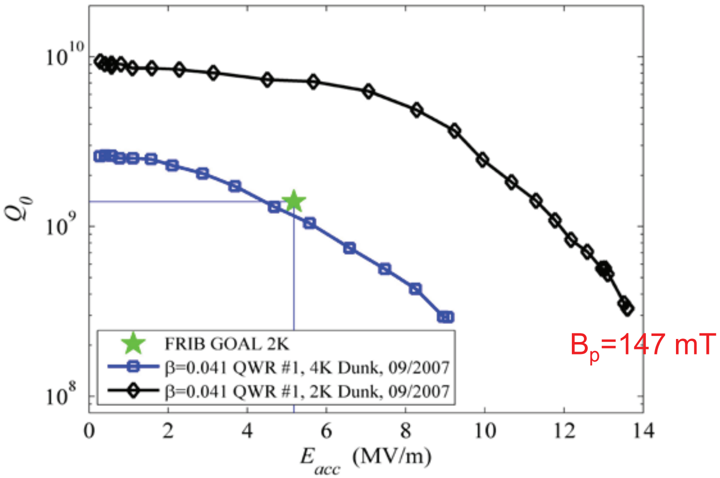
$\beta\lambda$=16 cm $\beta\lambda$=32 cm

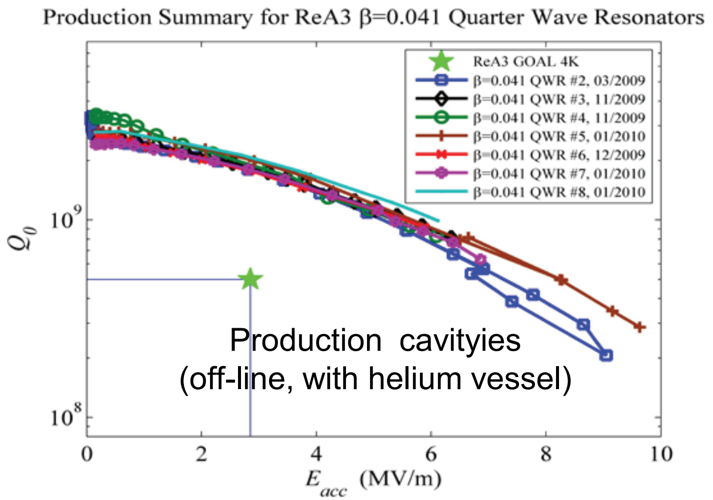
β_0=0.41 QWR – 2 Years of Operation in ReA3

- Naked test at 2 K
  - E_p=80 MV/m, B_p=147 mT
- Dressed test at 4.2K
  - All cavities beyond specifications
- In ReA3
  - 7 cavities operating on line at 4.5K and relatively low field as required (E_p=16 MV/m, B_p=35 mT)
- Similar results expected for the β=0.085 QWRs of similar design...

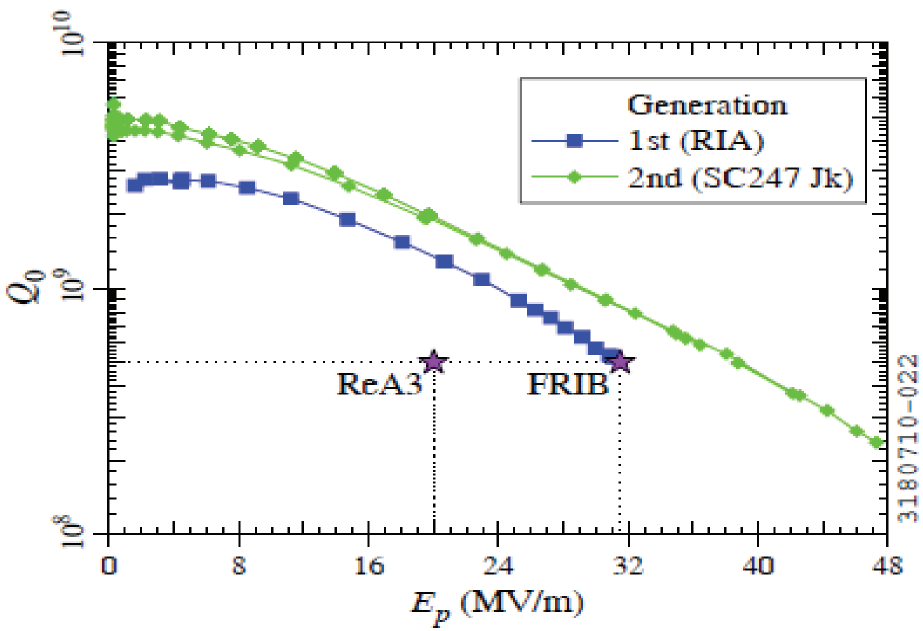


Best results
(naked prototype dunk test)





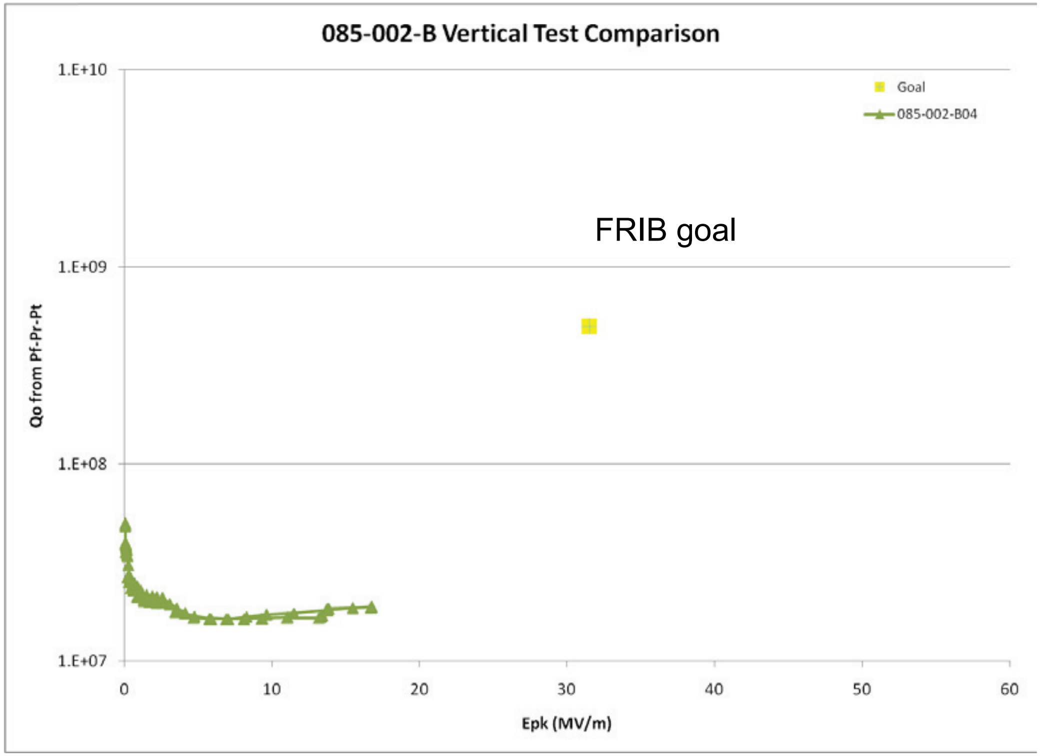
β=0.085 QWR Prototypes Performance



4.2K Results of the first β=0.085 (naked cavity – dunk test)
FRIB and ReA specifications are given for 4.2K

- Built 2, β=0.085 QWR prototypes without He vessel (naked)
- Tested fully immersed in liquid He (dunk test)
  - One performed well, as expected
  - One gave rather bad results
    - » initial interpretation: defect in the material hard to see, statistically possible
- The design was accepted
- 9 cavities built with He vessel

Irreproducible Results?



Cavity 246 RF test results at 4.2 K

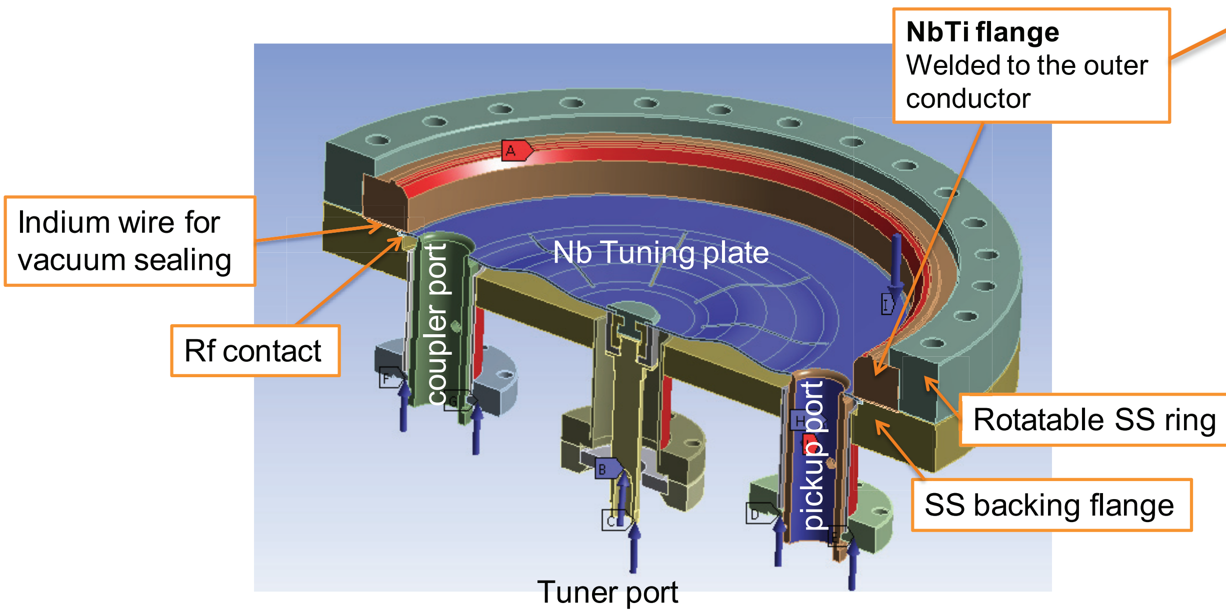
- 9 new cavities:
  - all much below specifications
  - Bad results also after He vessel removal
- “Good” prototype:
  - initial results irreproducible after He vessel installation
- Initial suspects:
  - Construction defects
  - Unwanted changes in cavity preparation
- No evidence found:
  - all cavities looked good
  - good results with the same processing in β=0.53 HWRs

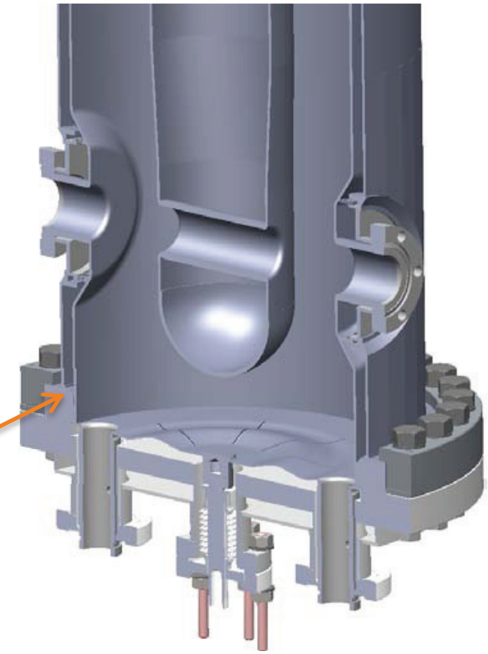
Search for the Problem Origin

- The problem appeared rather subtle and complex
- A panel of SRF experts from other laboratories were contacted and a weekly phone meeting was organized to discuss strategies and results (C. Crawford, P. Kneisel, R. Laxdal)
- We started an intense campaign in order to solve this problem which was leaving FRIB and ReA without one of their main components
- We used
  - Old data analysis
  - EM simulations
  - Thermal simulations
  - Cavity assembly procedure changes
  - Cavity surface treatments
  - Cavity thermal treatments
  - Cavity mechanical modifications
  - Cavity RF and thermal testing at different temperatures (38 RF tests, up to 2 cold tests per week, and a comparable number of CP and HPR treatments)

Prime suspect: bottom plate system

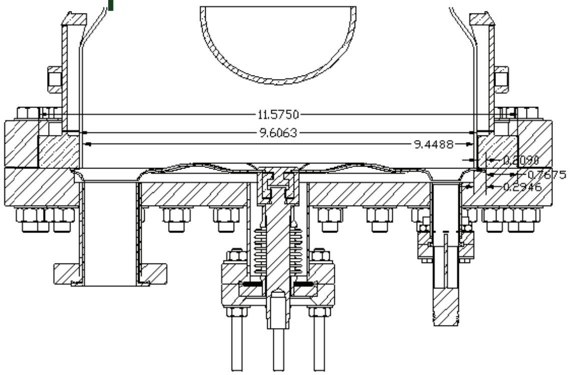
- Possible problem: normal conducting spots
  - Bad RF contacts
  - rf losses in the NbTi flange
  - Bad cooling, bottom plate overheating
  - RF losses in Coupler (glow discharge, MP…)
  - Field emission to coupler and tuning plate
- However, the same type of bottom plate was working well in the β=0.041QWRs…





RF Contact Tests

- The tuning plate hosted the rf ports and was cooled through the rf contact with the NbTi flange. The pressure was given by the SS backing flange
- The pressure on the rf contact was measured of by means of film



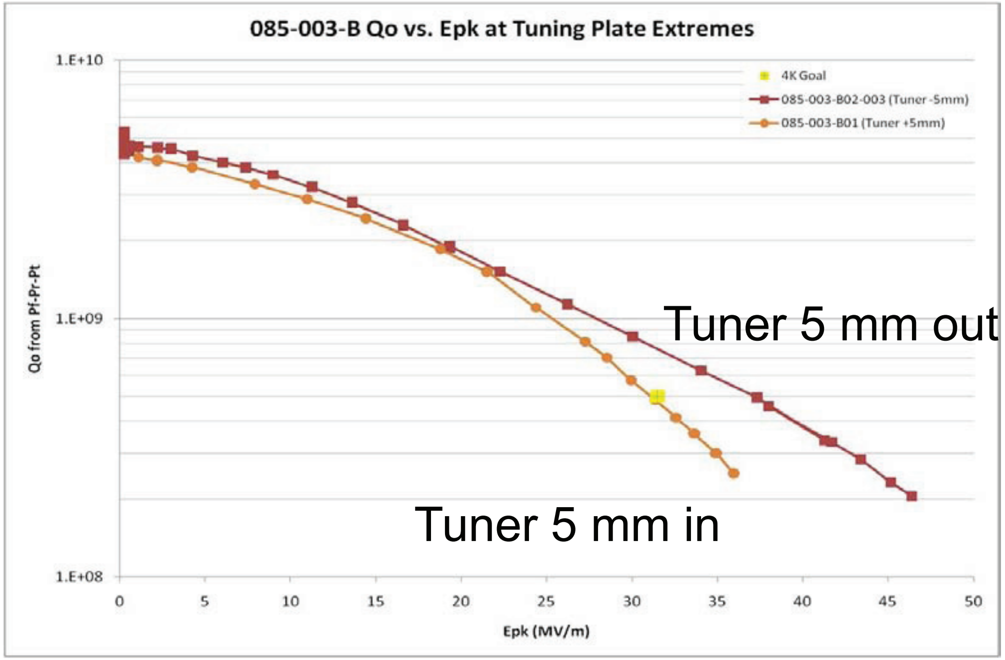
Good contact

Bad contact

  - Special rings have been inserted to increase that pressure
  - A special "knife edge" RF contact to the Nb outer conductor was tried
- More pressure in the contact was giving slightly better performance
- **None of these actions lead to good SRF results**

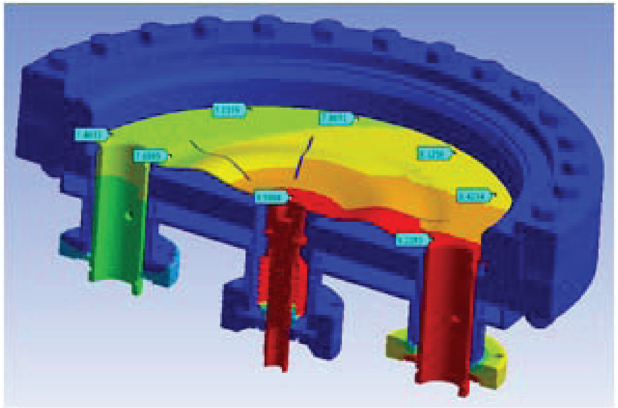
Role of the Plate-to-Inner Conductor Distance

- From old data analysis:
  - The "good" prototype could reach a higher field when the plate was retracted by the tuner far from the inner conductor tip, with no x-rays
- Overheating and NC spots due to rf current increase?



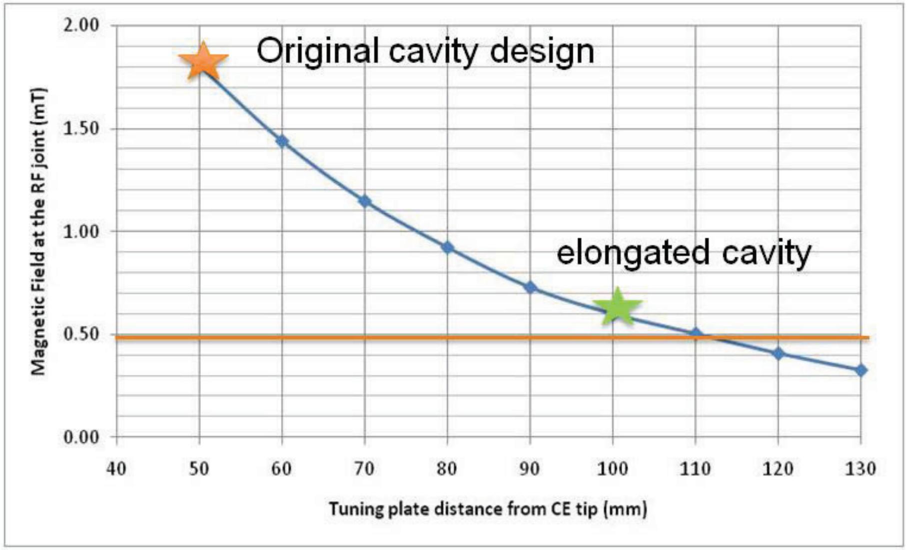
Heat Load from Coupler, Tuner?

- We suspected overheating and local SC to NC transition of the plate (in hot spots), due to
  1. RF coupler radiating heat on the plate, drained by thermal conduction along the thin Nb plate and dissipated on NbTi flange
- Simulations: coupler+tuner heat load to the tuning plate ~ 1 Watt: not too bad, as in the working β=0.041 QWR
- Sufficient cooling in the β=0.041 QWR, but not in the β=0.085 one even when fully immersed in liquid He?



Too High Magnetic Field in the RF joint?

- Suspect: ~2 mT magnetic field in the normal conducting RF joint too high?
- "Comfortably safe" value from experience: ~ 0.5 mT

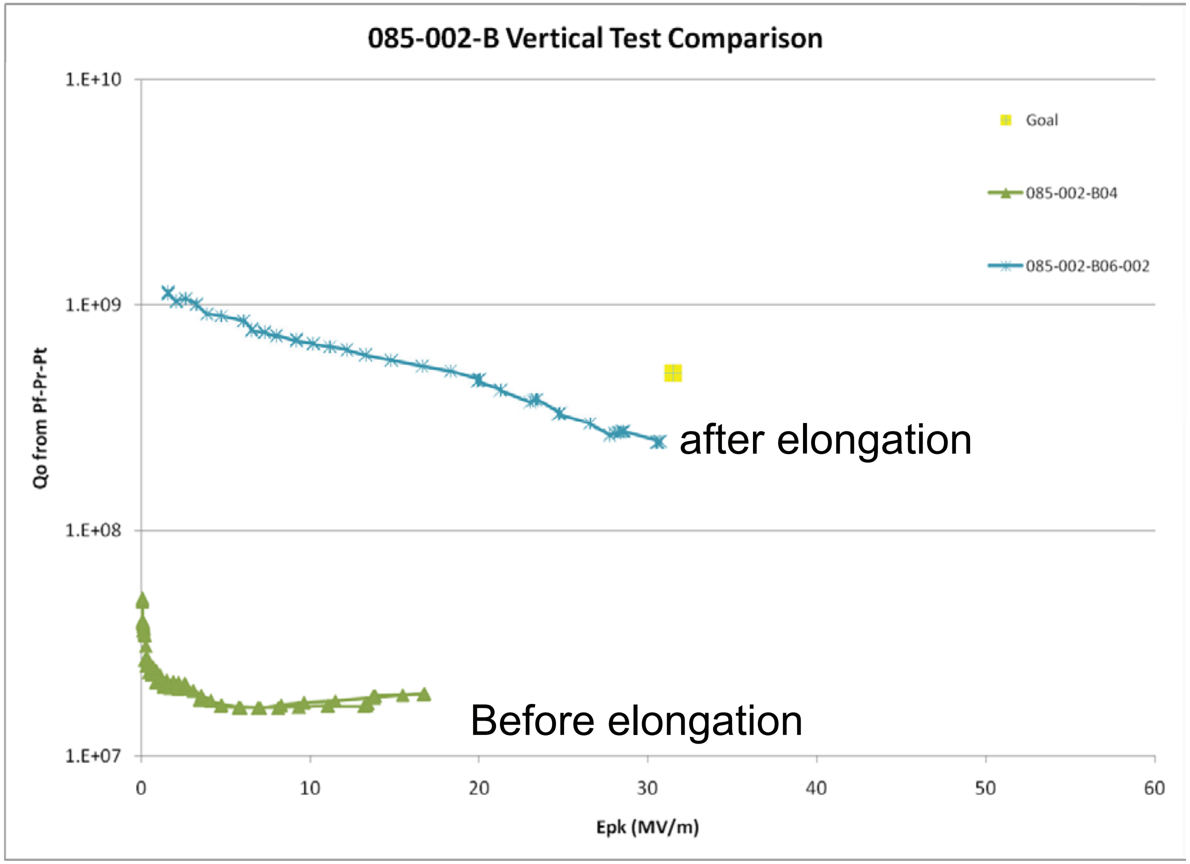


Critical test: elongation of the cavity OC

- Added 5 cm to the OC of the worst performing cavity
  - 0.5 mT in the RF joint at the FRIB E_a
  - lower E_p , lower field emission to the plate
  - lower rf current on the plate thus lower rf losses

Improvement with Elongated Cavity

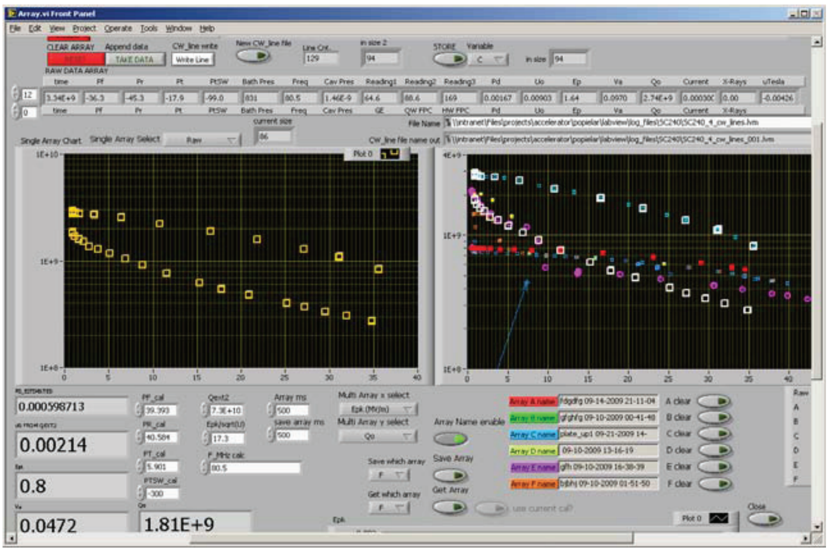
- Q and E_a
  - Before elongation: very bad
  - After elongation: great improvement
  - The cavity could not yet reach specifications

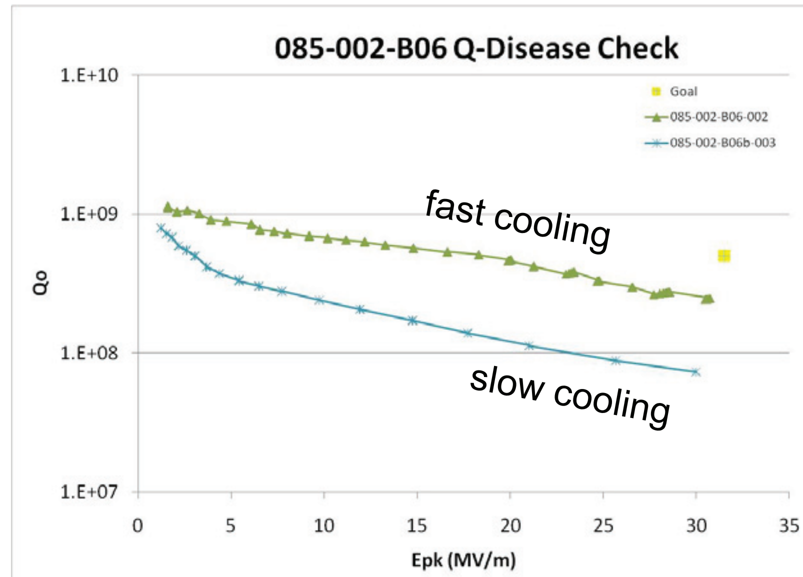


- **Plate-IC distance critical parameter**, but main limiting factor still unknown
  - What about Q-disease? Could it randomly contribute giving misleading results?

Q-disease

- We did various “12 hours 100K soaking” tests in order to verify if the cavity was affected by Q-disease
  - The cavity showed a strong Q-disease

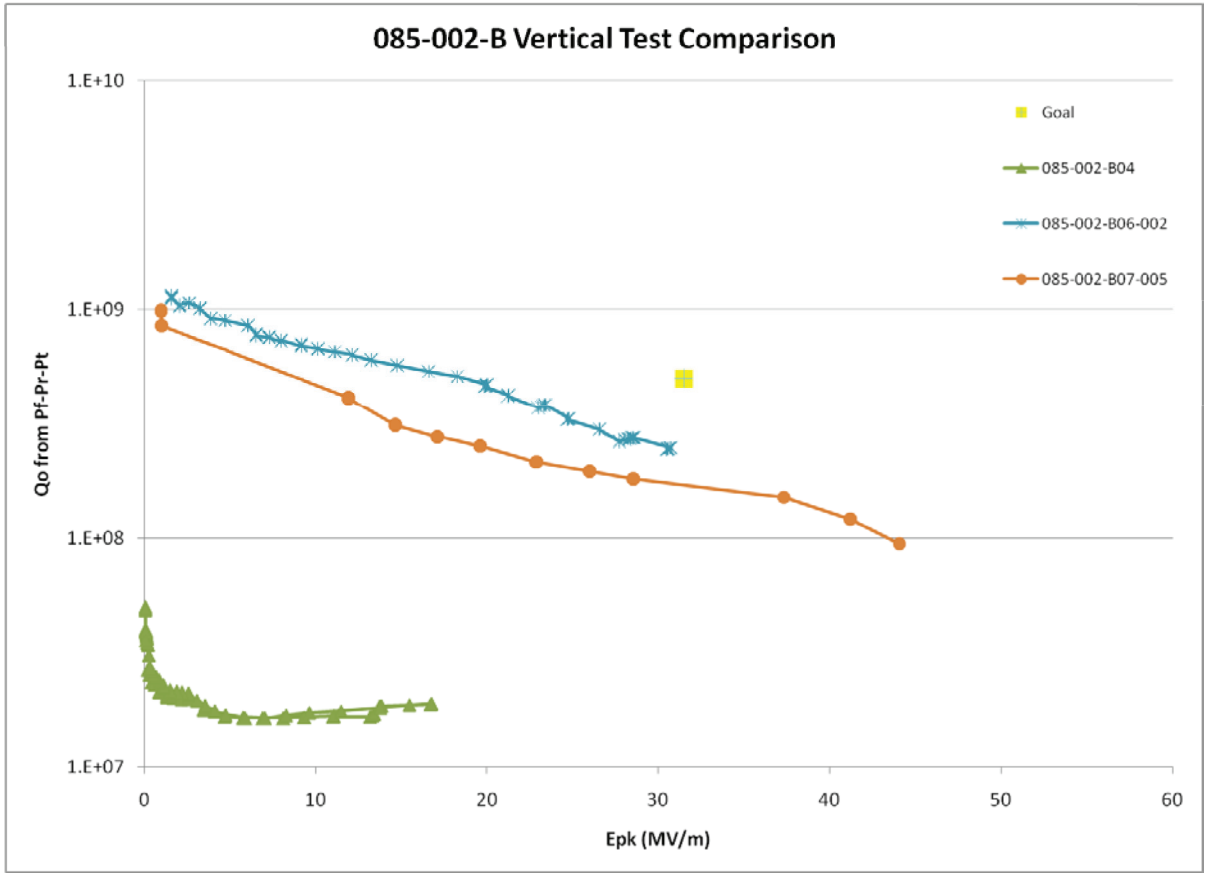




- We treated the elongated cavity at 600 C for H degassing
- The heat treatment was performed by JLab

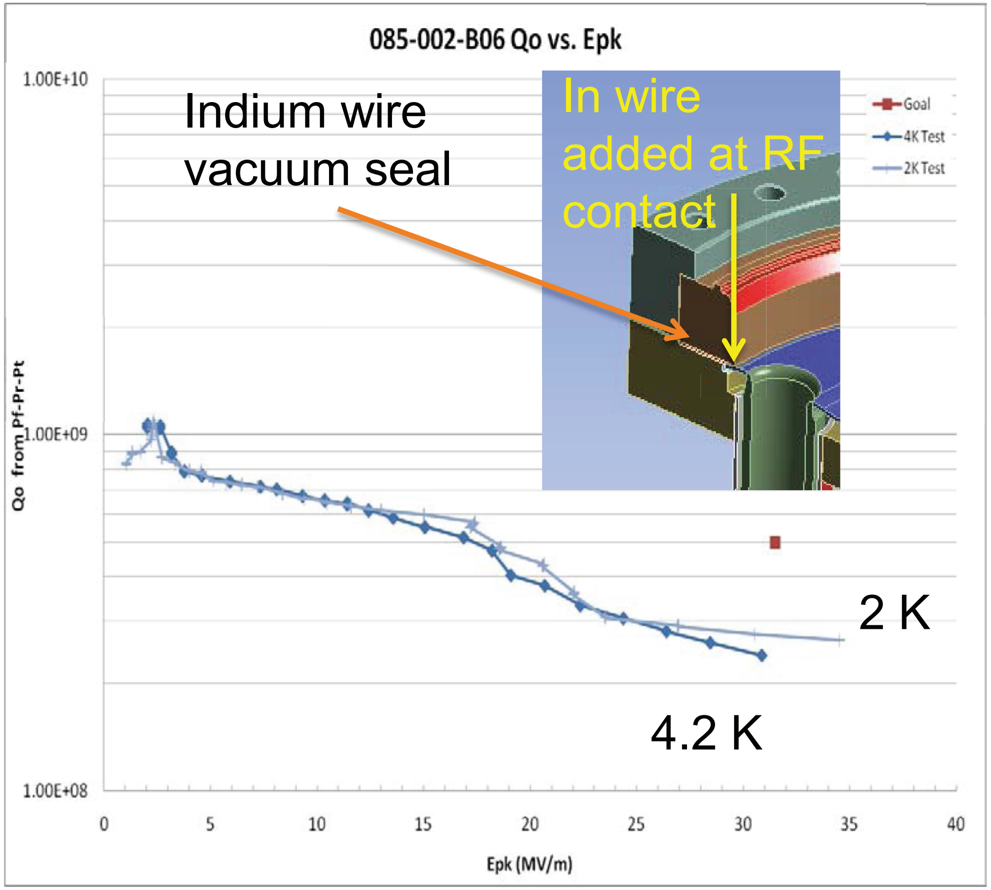
600° Hydrogen Degassing Results

- Q disease disappeared
- E_a above specifications
- No progress in Q: presence of <u>another source of strong RF losses</u>
- Suspect: RF current flowing beyond the RF contact, on the SS backing flange?



RF Contact: 1st critical test

- We put an additional Indium wire close to the inner edge of the cavity flange, to fill possible gaps and make a good RF contact
- We tested down to 2 K
  - Same results at 2 and 4.2K
  - No Q jump at 3.4 K, Indium T_c
- Rf current flowing beyond the wire over SS could explain the rather constant losses at 2 and 4.2 K and the very low Q
- **RF contact was not at the inner Indium wire?**

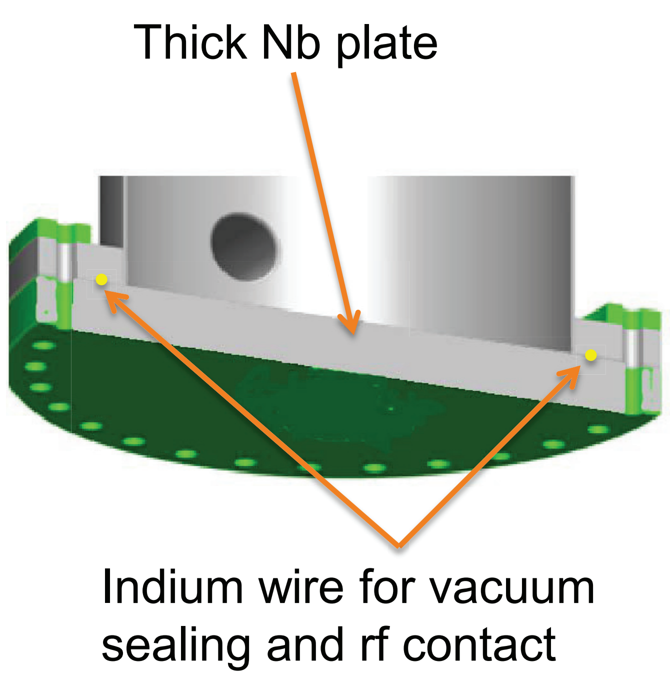


Rf contact: 2nd Critical test single In wire and thick Nb plate

- New suspect: differential thermal contraction of SS and NbTi (0.5 mm) could cause opening of the RF contact while cooling down the cavity

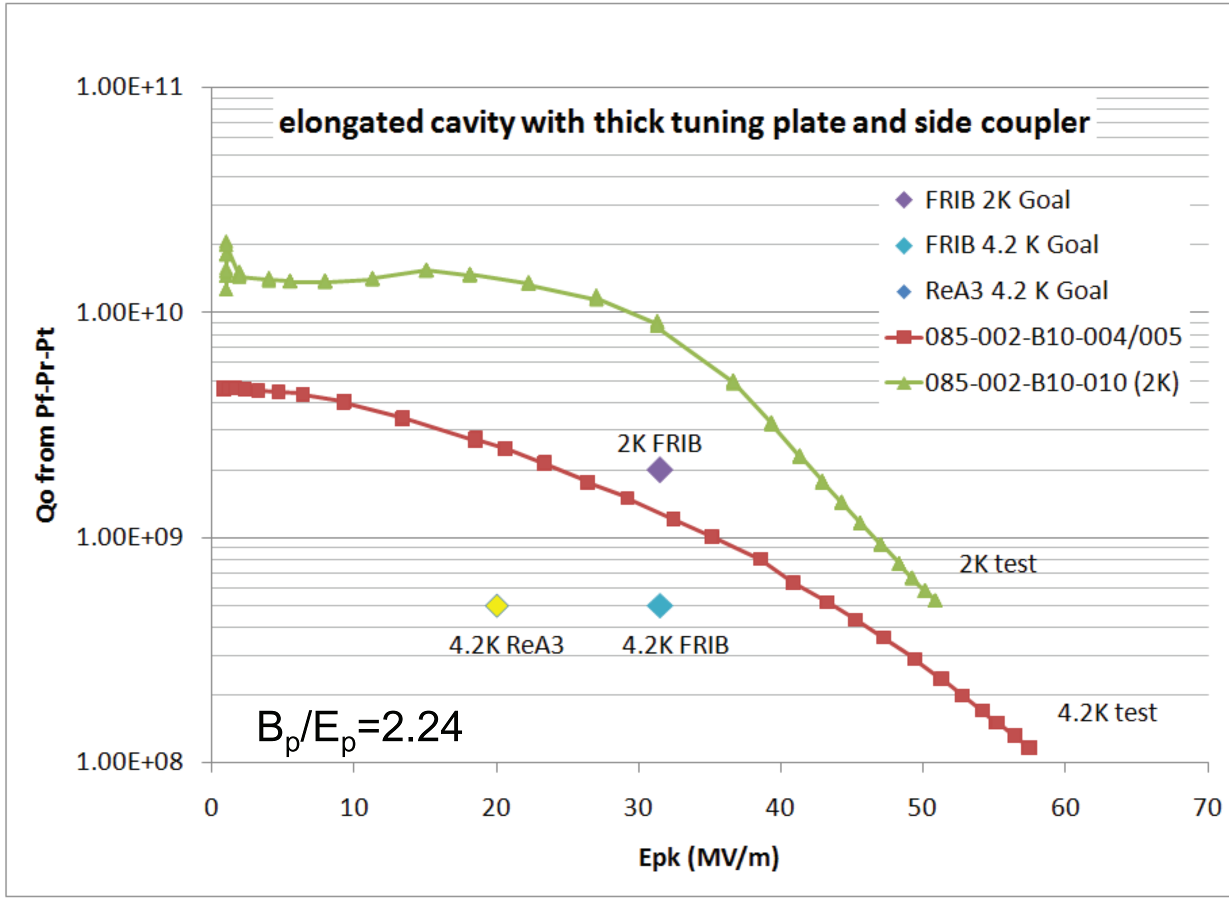
2nd Critical test:

- Rf couplers mounted at beam ports
- thin Nb plate and SS backing flange replaced with a single, thick Nb plate:
  - **differential contraction removed**
- Single In wire between NbTi flange and Nb plate:
  - **good vacuum ⇒ good rf contact**



The Culprit was finally caught…

- Excellent Q at 4.2K and 2K with the "bad" QWR after elongation and plate modification
- FRIB specifications fulfilled with a large margin both at 4.2 K and 2 K
- Problem understood
- Solutions were available



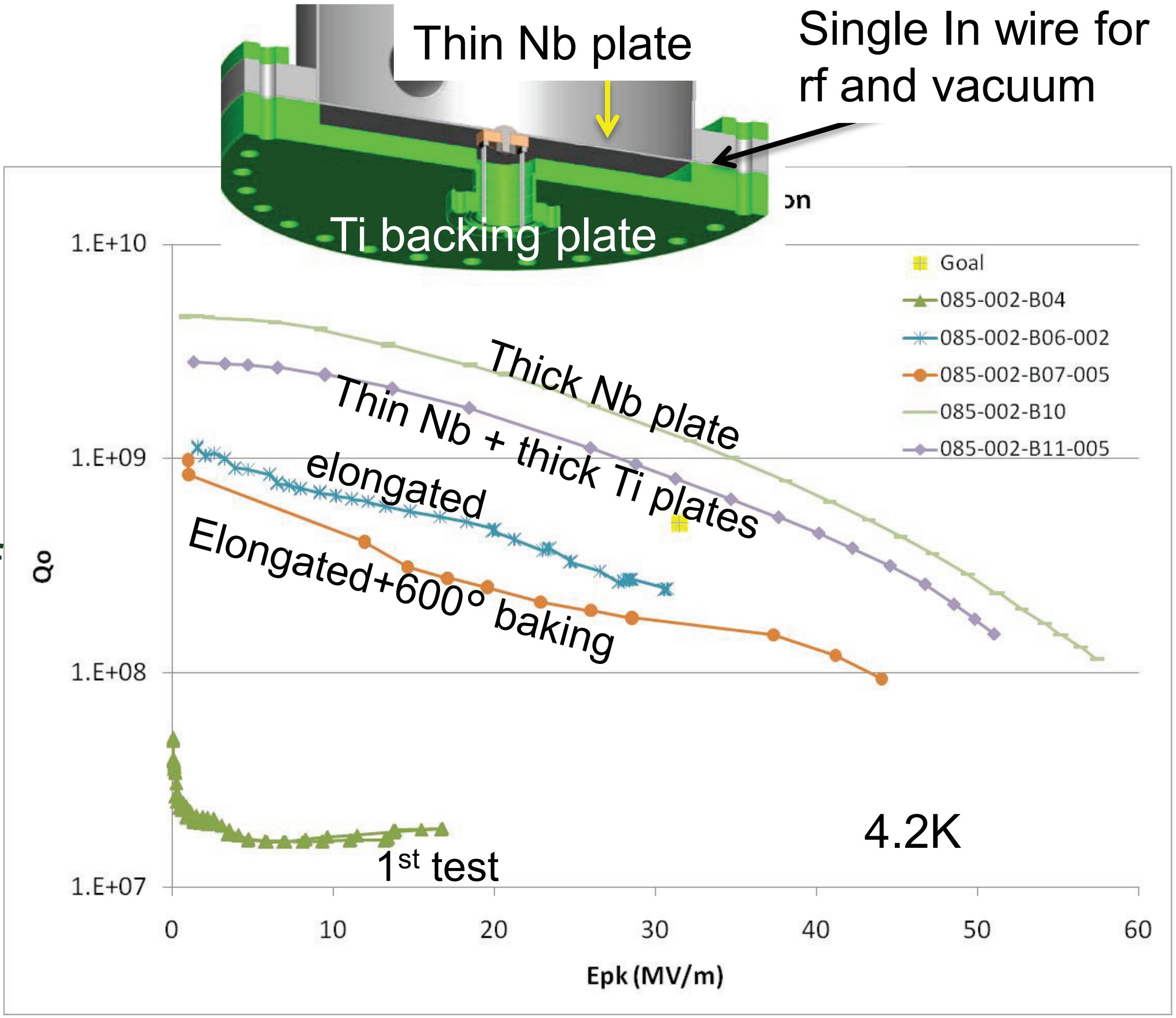
4.2 and 2 K naked results of resonator 246 (elongated) with single Indium wire and thick Nb plate

Naked Test with RealisticTuning Plate

- The 20 mm thick Nb plate could not simulate the real, 1.2mm tuning plate

New test with:

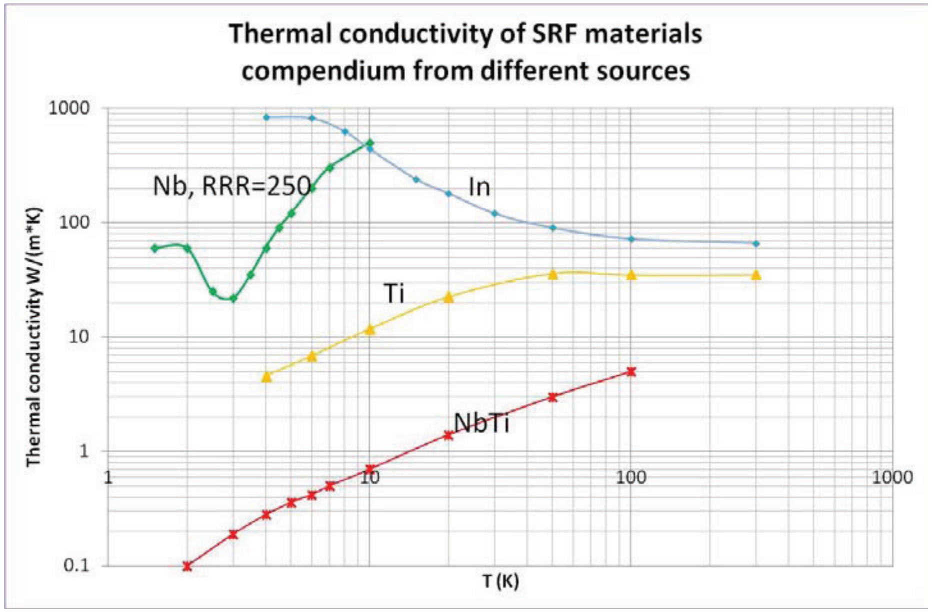
- **1.2 mm Nb tuning plate**
- **Titanium baking plate** to remove the problem of differential contraction
- Results good, but lower Q and earlier quench: **plate cooling issues?**



Thermal Issues with the NbTi Bottom Flange

The Nb tuning plate is cooled by the bottom flange through the Indium seal: bad cooling could turn in NC spots

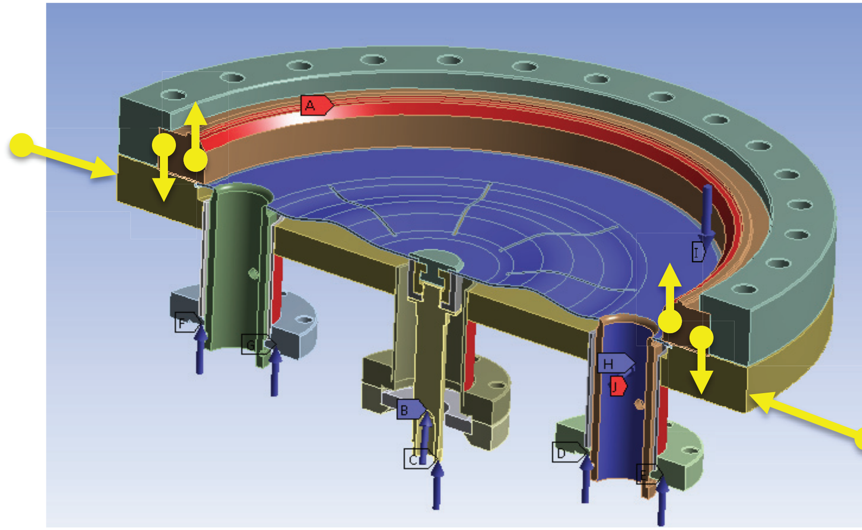
- Thermal conductivities at cryogenic T:
  - Indium: excellent
  - High RRR NB: quite good
  - NbTi : quite bad
- NbTi flange:
  - Relatively cheap
  - it welds well both with Nb and Ti
- **High RRR Nb flange: more expensive than NbTi, but necessary for efficient cooling of the tuning plate**



Final Diagnosis: Multiple Illness

- differential thermal contraction of the NbTi flange and SS backing plate caused the conical deformation of the NbTi flange and opening of the RF contact during cooldown

- The current flowed in the RF joint through SS in a hardly controllable way.

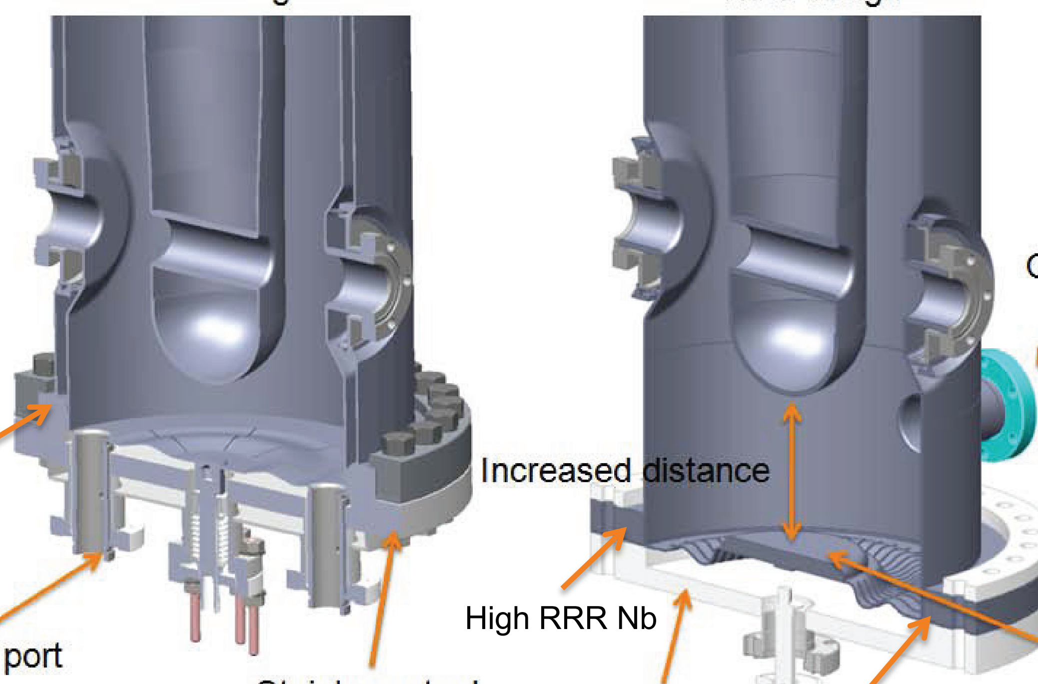


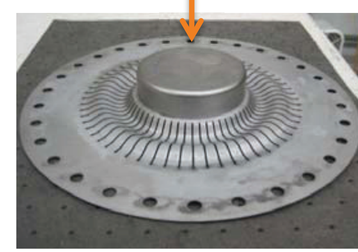
- The short inner conductor tip - tuning plate distance caused
  - High current flow through the bad RF joint, plate overheating
  - High peak E field on the tuning plate, FE
- The RF couplers on the tuning plate increased thermal load
- The low thermal conductivity of the NbTi flange caused bad cooling

Therapy ⇒replacing the bottom plate system

Refurbished Cavity Design for ReA3

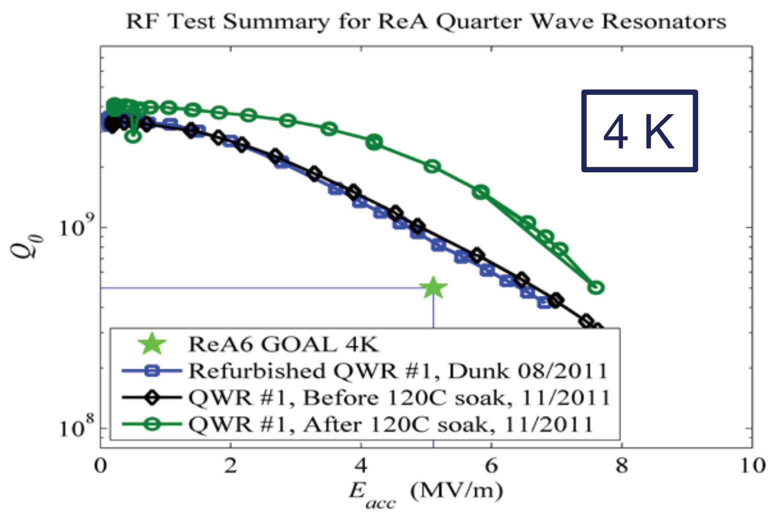
- The plate and rf ports positions were optimized to obtain low rf losses, low B at rf joint and a tuning range of ±20 kHz
- A new slotted plate was chosen, with adjustable puck for final tuning

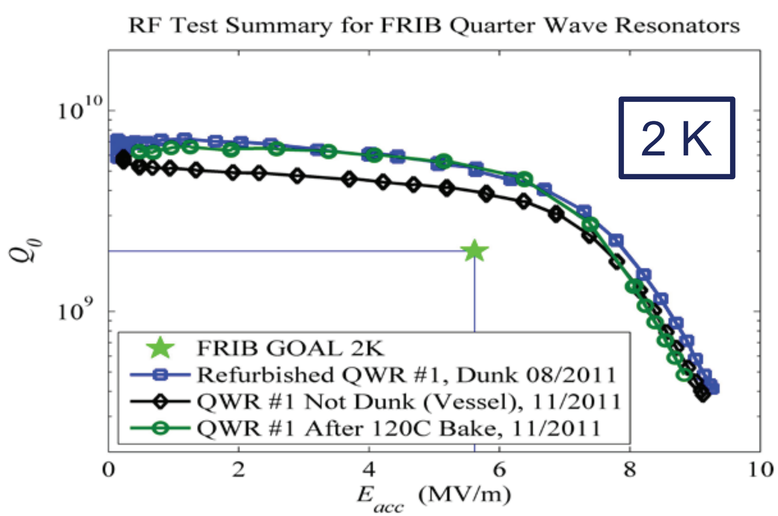




First Refurbished QWR Performance with Low Temperature Baking

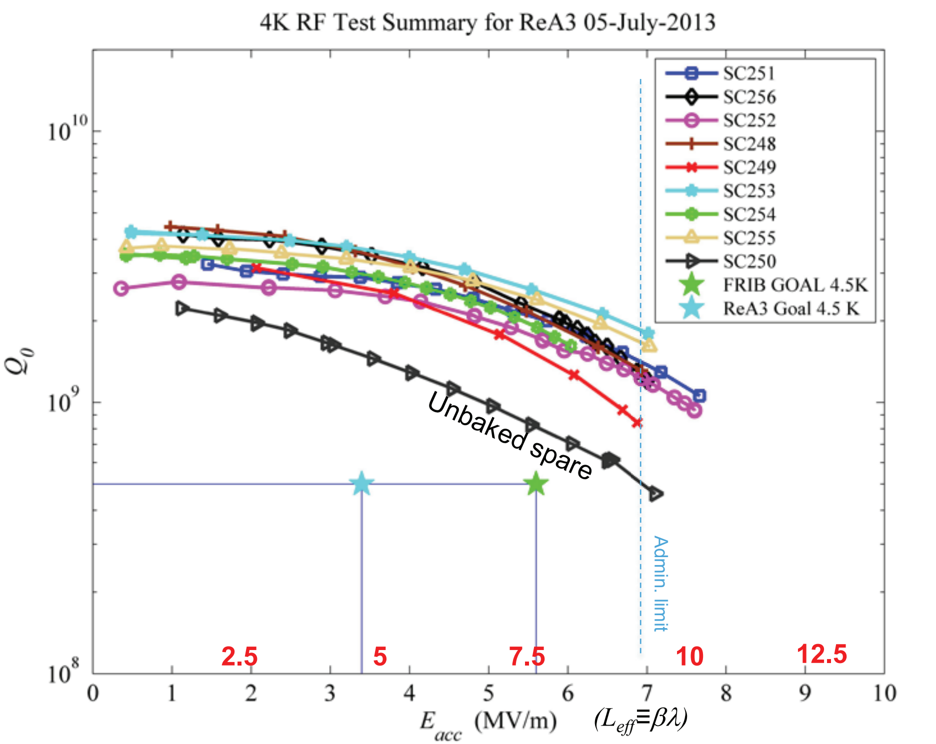
- A first, fully refurbished cavity with high RRR Nb bottom flange was obtained by modifying the old “good” prototype
- Excellent results were obtained both with the naked and, for the first time, with the dressed cavity
- Low temperature baking at 120° C improved Q at high E_a
- All 9 QWRs for ReA3 were refurbished

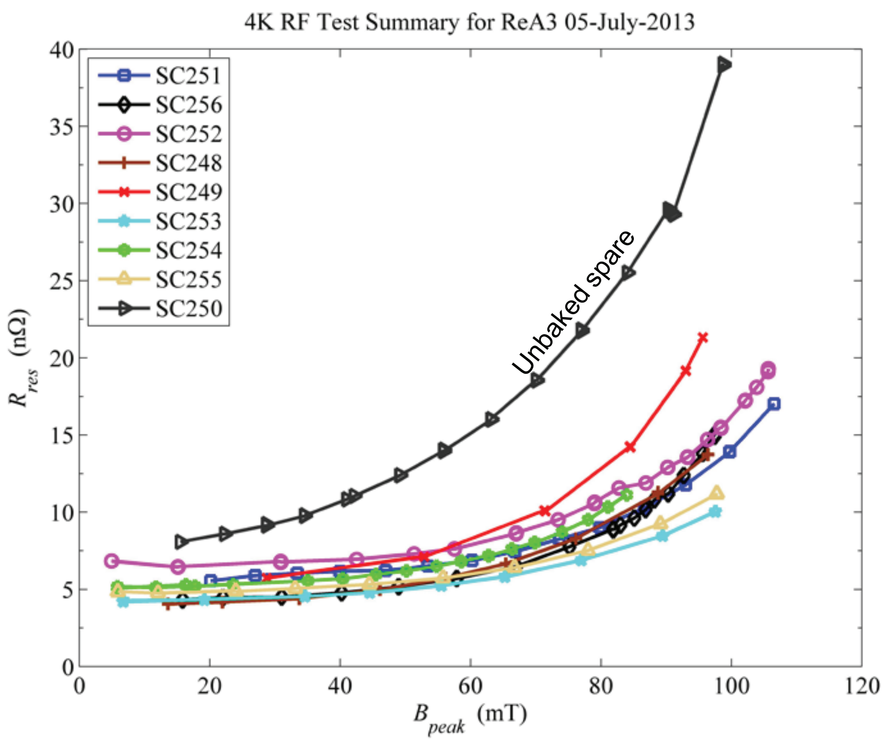




Final Performance at 4.2 K of the 9 ReA3 Refurbished QWRs

- All refurbished QWRs exceeded ReA specifications at 4.2K with uniform and reproducible performance after 120° C baking





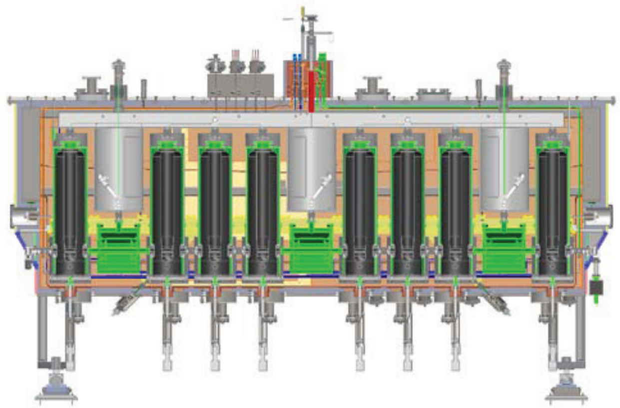
Red marks: with L_{eff}=240 mm cavity diameter < $\beta\lambda$=317 mm

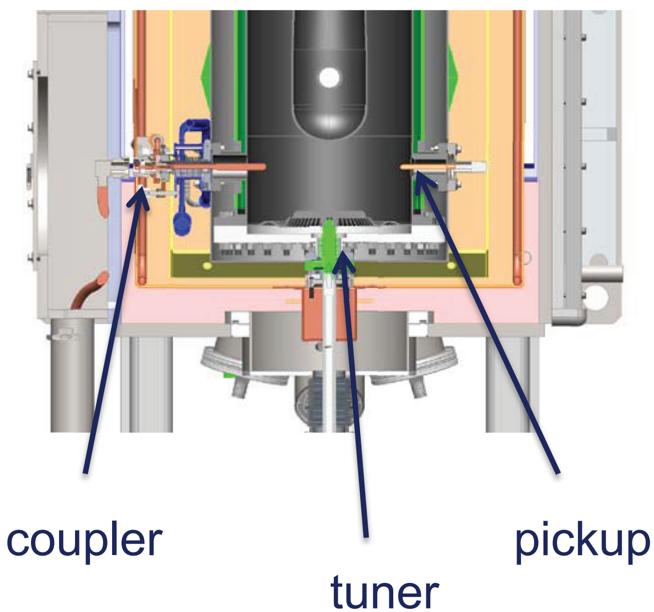
7 MV/m is an administration limit applied during vertical test before installation

β=0.085 ReA3 Cryomodule

- Refurbishment of existing ReA3 cavities successfully completed
- All cavities exceeding specifications both for ReA and FRIB
- Construction of ReA3 cryomodule with MSU side couplers close to completion

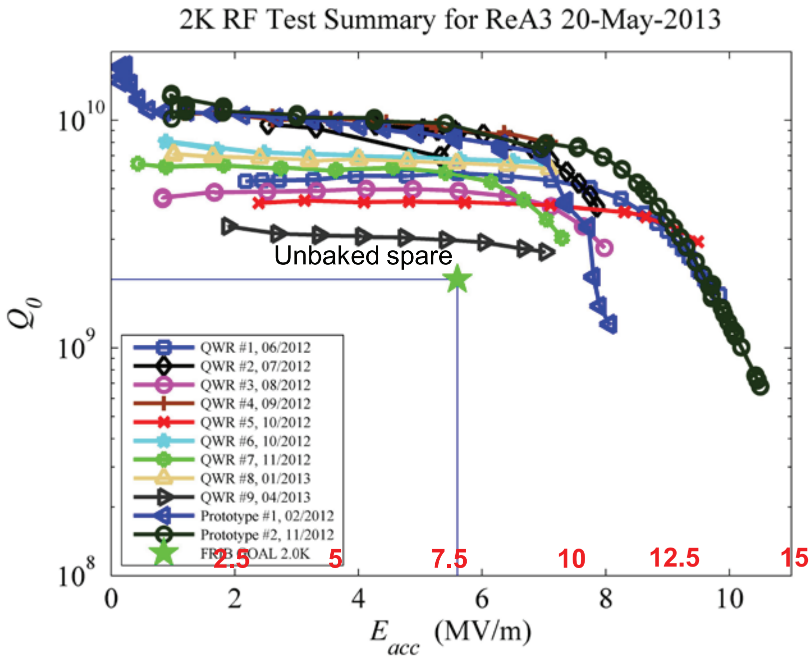
ReA3 cryomodule

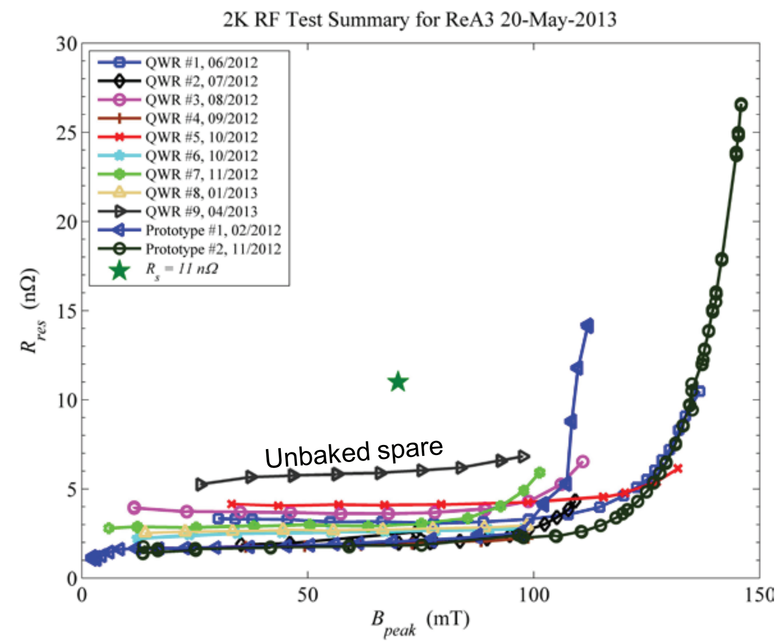




ReA3 QWRs Performance at 2K

- Two prototypes and nine production cavities tested at 100% success rate since 2011
- **FRIB requirements largely exceeded at 2K**
- The FRIB QWRs will be similar, with larger OC diameter

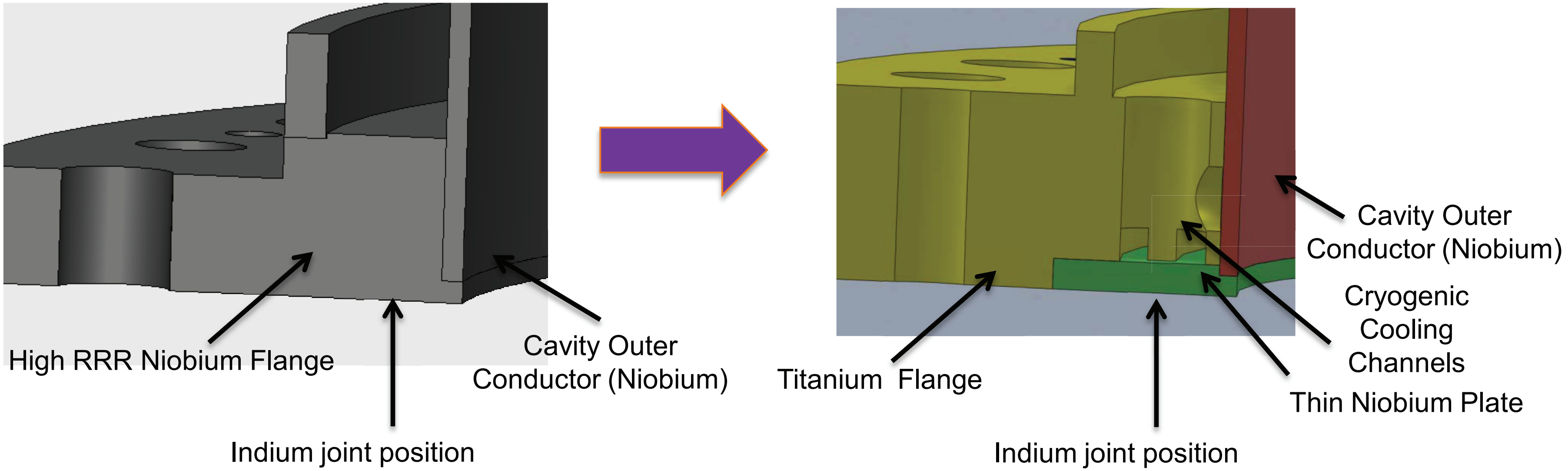




Red marks: with L_{eff}=240 mm cavity diameter < βλ=317 mm

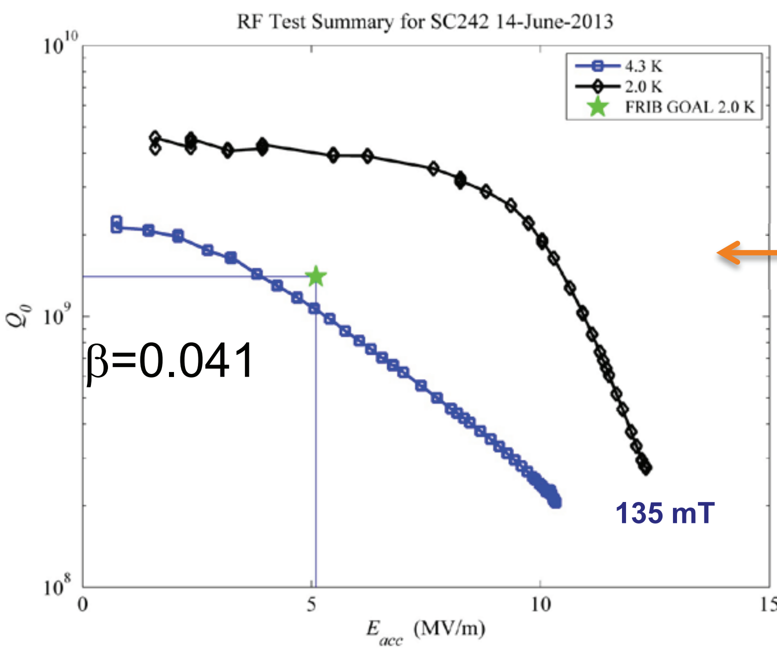
Low Cost Bottom Flange for FRIB QWRs

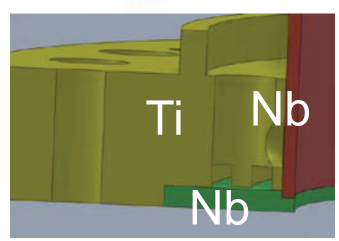
- New, high RRR Nb flange: very well performing, but requiring a large amount of expensive material (~350×350×20 mm plates)
- We made the same flange with Ti material, and only a small amount of high RRR Nb in the area of the Indium joint exposed to RF
- Good cooling is guaranteed by channels for liquid He
- The flange cost was drastically reduced by 90%

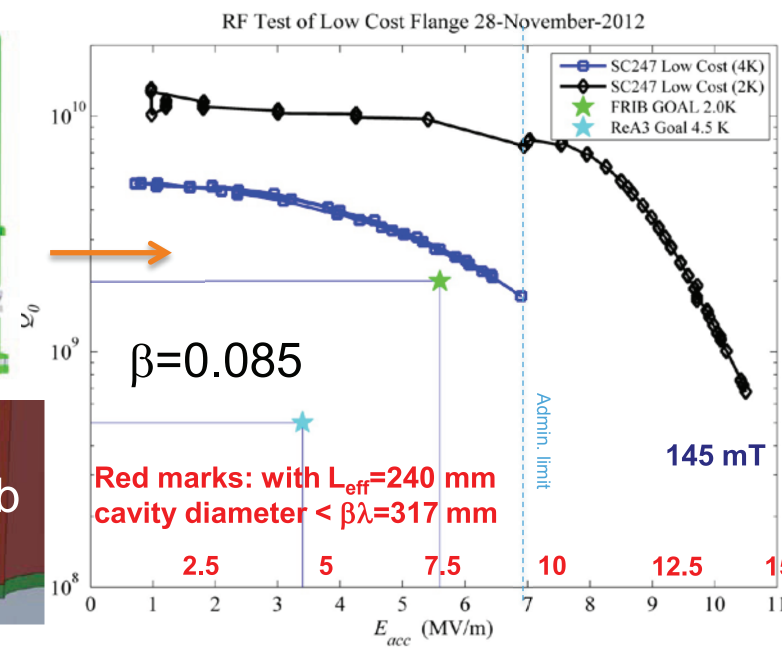


Low cost flange results

- Low cost flanges were tested in both ReA3 β=0.041 and β=0.085 QWRs equipped with He vessel
- Results largely beyond FRIB specifications
- Adopted as baseline for the FRIB QWRs with significant cost savings







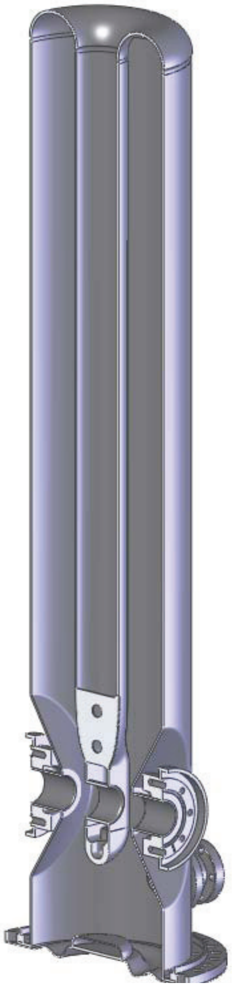
Results at 4.2 and 2K of ReA3, β=0.041 and β=0.085 QWRs with He vessel, limited by available rf power

Last questions to bring the puzzle to a solution..

- Why the standard configuration worked well in the β=0.041 and not in the β=0.085 QWRs?
  - β=0.041 QWR:
    - » smaller outer conductor diameter
    - » smaller IC tip surface

1. lower current induced by capacitance to the plate: lower thermal load
2. Shorter cooling path : better cooling
3. lower differential contraction: better rf contact

- Is it worth to refurbish also the β=0.041 QWRs for FRIB?
  - Further testing showed slow cooling even in the β=0.041 cavity tuning plate: problems might appear at the FRIB gradients
  - **the FRIB lower-β QWRs will have the new design**



Conclusions

- Subtle phenomena can cause sometimes big trouble and large delays. A similar problem appeared in the ReA QWRs after apparently insignificant modifications of a working design, which were expected to preserve performance without drawbacks and without need of systematic testing.
- Eleven underperforming QWRs of the first ReA3 production lot could be fully recovered by detecting and fixing the several design details that, combined together, caused a somehow puzzling behaviour.
- This work, in addition to bringing ReA resonators to full performance, gave us precious information for the design of the FRIB resonators and for the assessment of their optimum processing.

Acnowledgments

- We thank C. Crawford, P. Kneisel and R. Laxdal for their valuable advice during weekly teleconferences

"Every puzzle looks easy once you know the solution"

Thank you