TRIUMF

Canada's national laboratory
for particle and nuclear physics
and accelerator-based science

An Overview of Recent Developments in SRF Technology

Bob Laxdal, TRIUMF

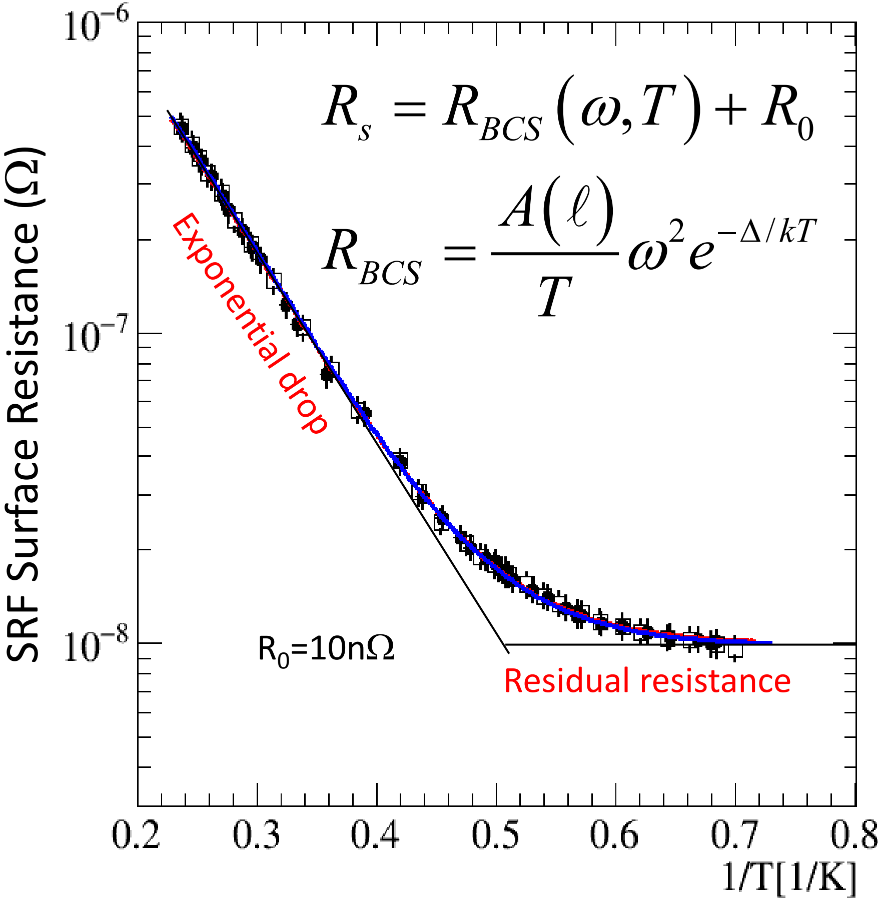
MO1A02, LINAC2018, Sept. 17, 2018

Outline

- Introduction to SRF
- Elliptical cavities
  - High Q and High Gradient
    - Doping, Infusion, Magic
    - Flux expulsion
    - Frequency dependence
- Non-elliptical cavities
  - High performance
  - New Structures
- Technical advances
- Future path

Introduction to SRF

SRF surface resistance



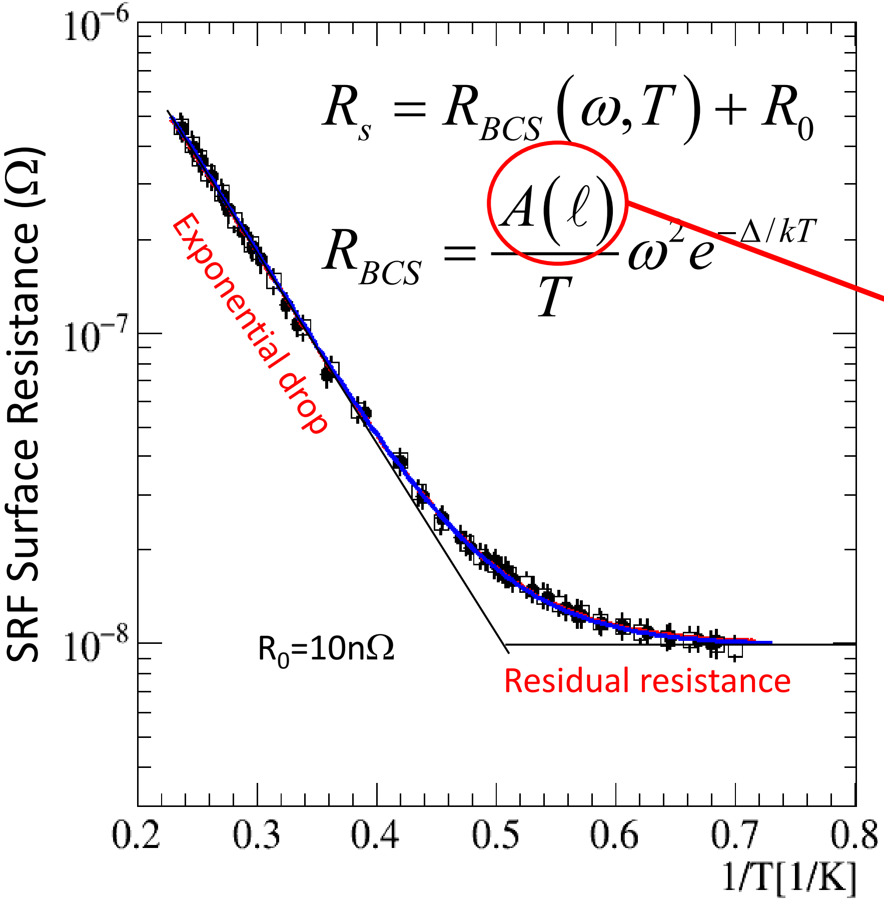
$$Q = \frac{G}{R_s}$$

constant

SRF surface resistance

$$R_s = R_{BCS}(\omega, T) + R_0$$

$$R_{BCS} = \frac{A(\ell)}{T}\omega^2 e^{-\Delta/kT}$$



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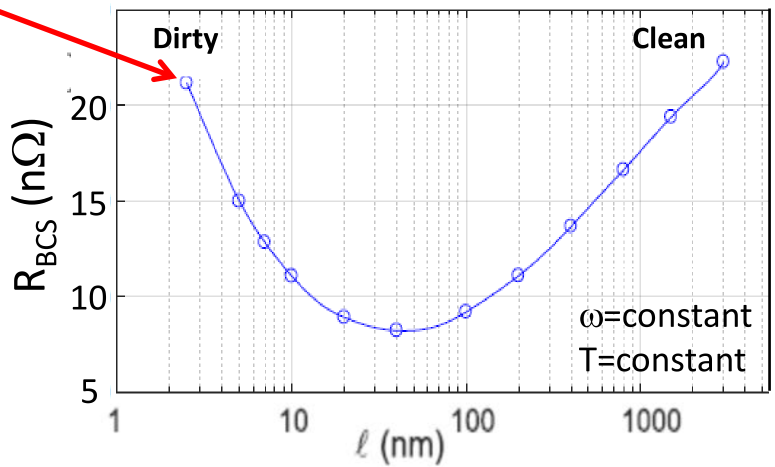
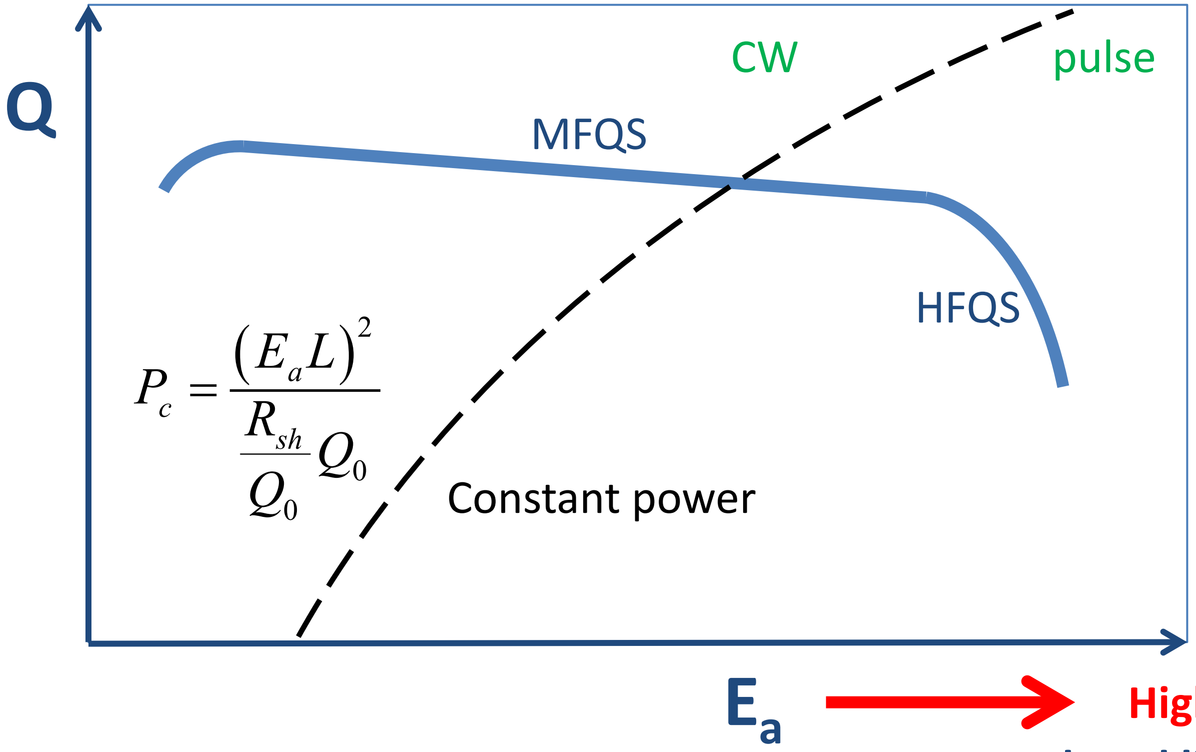


RBCS is dependent on ℓ, the electron mean free path

Optimization



Higher Q

Reduced operating costs

Higher gradient

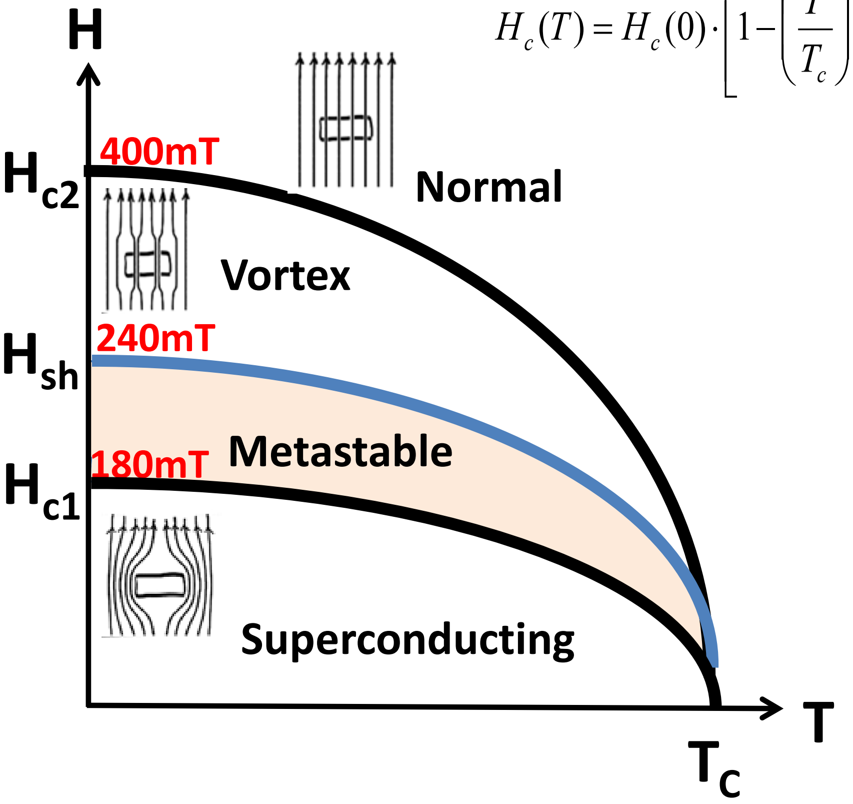
Reduced linac length – lower capital cost

Superconducting (H,T) Space for Niobium

Niobium is a Type II superconductor

- SC state: 0 → H_{c1}
- Vortex state: H_{c1} → H_{c2}
- Meta-stable state: H_{c1} → H_{SH}
  - surface energy barrier can inhibit vortex nucleation
- Flux vortices cause rf heating

$$H_c(T) = H_c(0) \cdot \left[1 - \left(\frac{T}{T_c}\right)^2\right]$$



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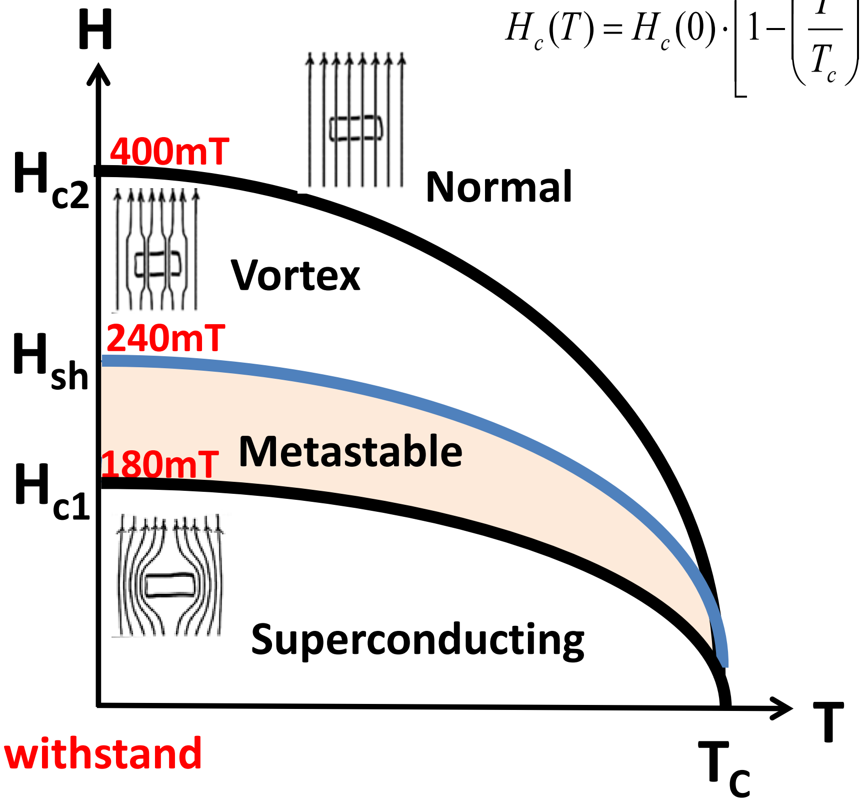
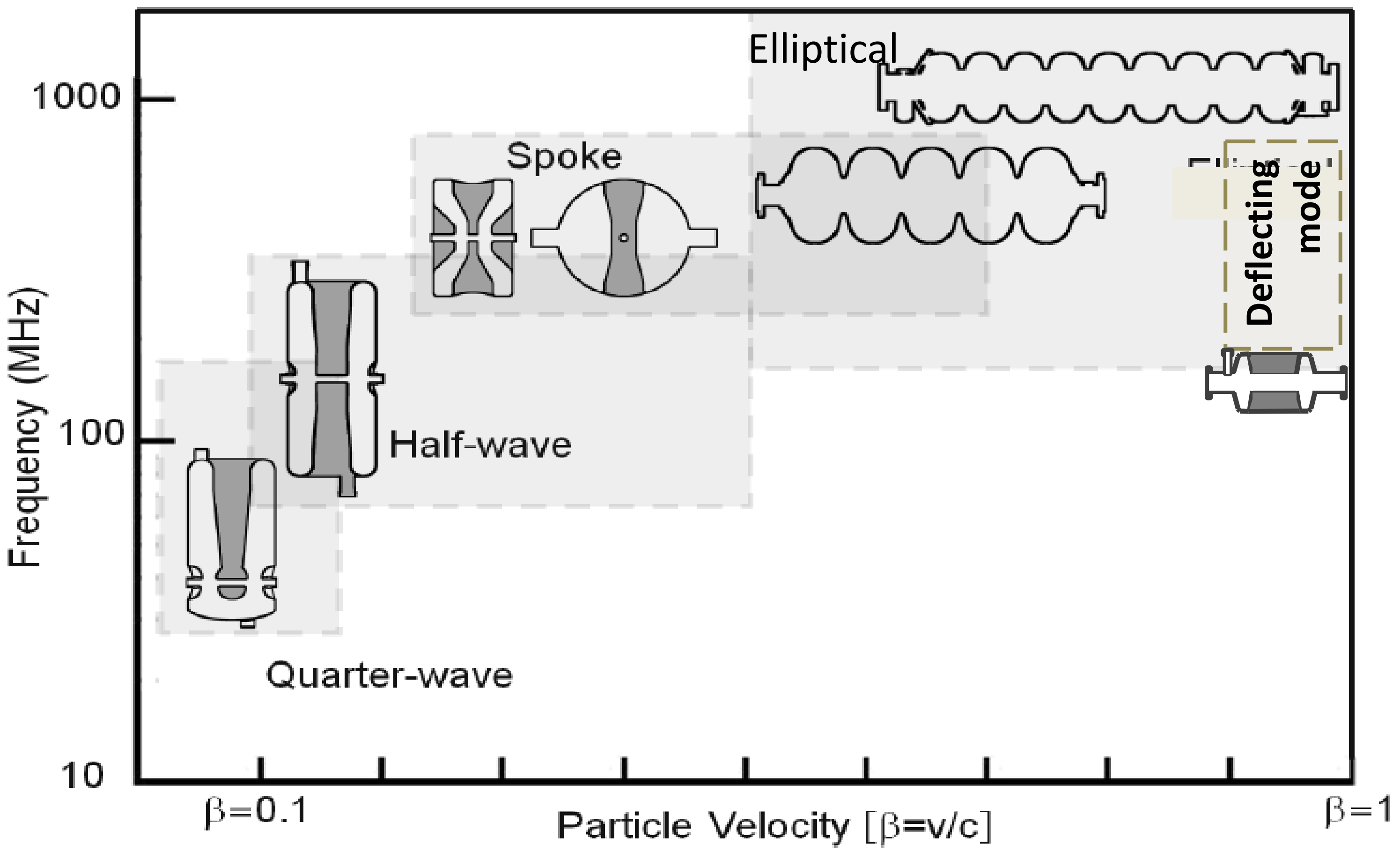


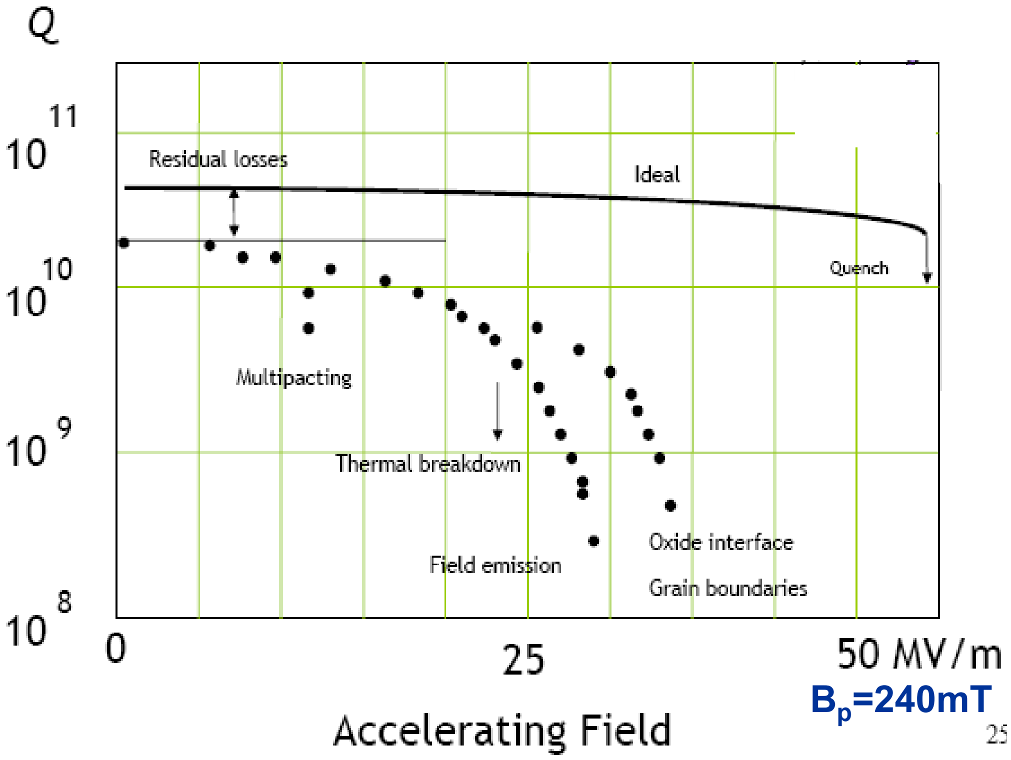
For high gradient we need a material that can withstand vortex penetration up to a high magnetic field.

SRF cavities – velocity and frequency range



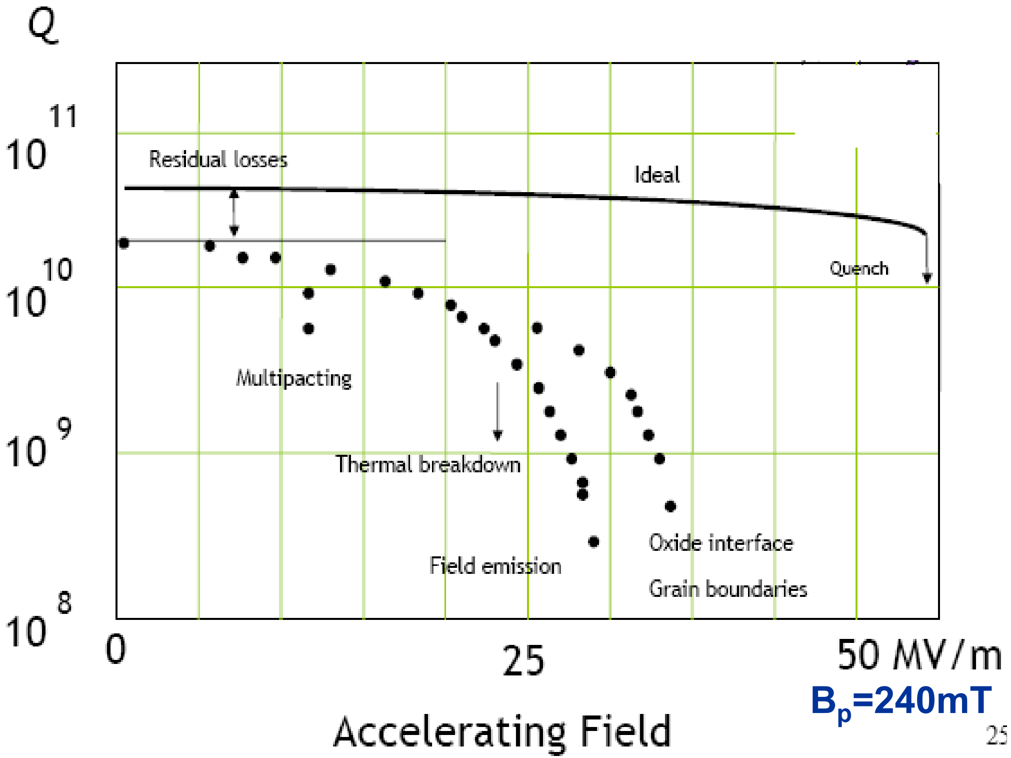
SRF performance limitations

- The SRF surface resistance is so low that it is easy to make it worse
- Some causes of reduced performance are:
    - Niobium insufficiently pure – inclusions of lossy material
    - Insufficient cleaning – particulates, chemical residues
    - Trapped magnetic flux
    - Q-Disease – too much hydrogen in material



SRF performance limitations

- The SRF surface resistance is so low that it is easy to make it worse
- Some causes of reduced performance are:
  - Niobium insufficiently pure – inclusions of lossy material
  - **RRR Material – EB welding**
  - Insufficient cleaning – particulates, chemical residues
  - **US degrease - High pressure water rinse (HPWR)**
  - Trapped magnetic flux
  - **Mu metal**
  - Q-Disease – too much hydrogen in material
  - **Hydrogen degassing 600-800C**



Where are we?

- XFEL is successfully completed – many projects on the go
- Projects can drive SRF development and SRF developments can enable projects
- XFEL (ILC) research has been very successful at pushing 1.3GHz technology to high gradient performance
- Many of the techniques developed for XFEL are being applied successfully in both elliptical and non-elliptical cavities

Timeline	Elliptical	Non-elliptical
Recent past	XFEL	FRIB
Present	LCLS-II	ESS, RISP
Future	EIC, ILC	PIP-II, ADS

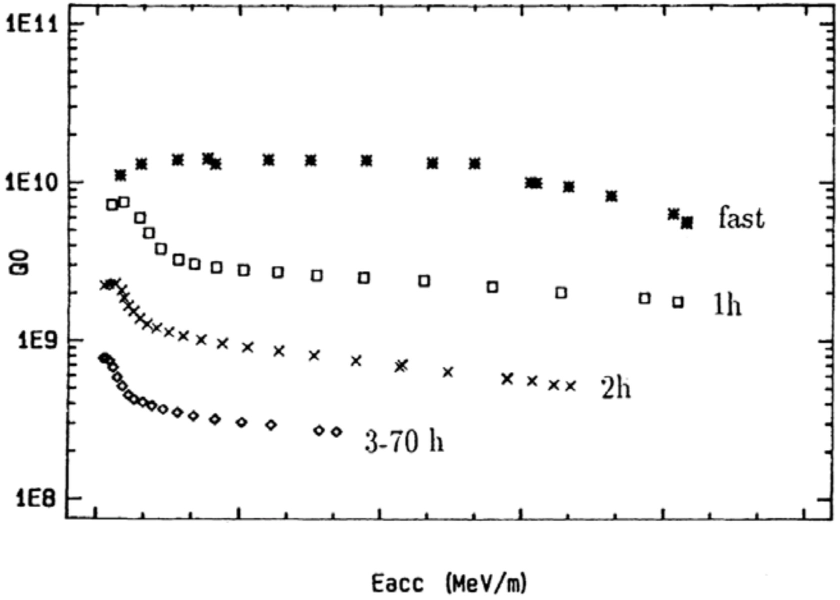
	N_{cavs}	Average	RMS
VT	815	28.3 MV/m	3.5
CM	815	27.5 MV/m	4.8

XFEL cavity useful gradient in vertical test and in cryomodule (goal 23.6MV/m)

See Talk FR2A02

Global Baseline - 800C degas

- Baseline – 140micron electro-polish (EP) or BCP plus 600 - 800C degas to reduce hydrogen concentration in Niobium and avoid Q-disease – all cavity types benefit from this degassing



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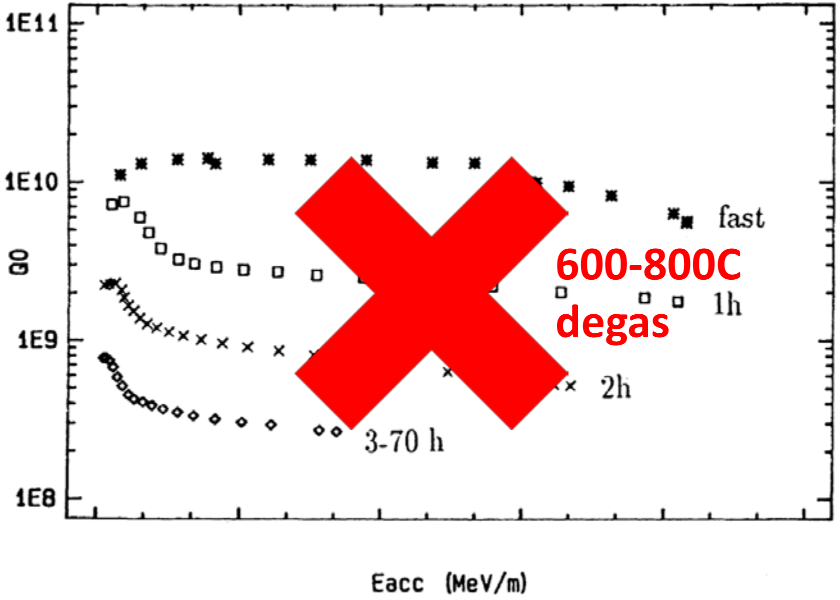
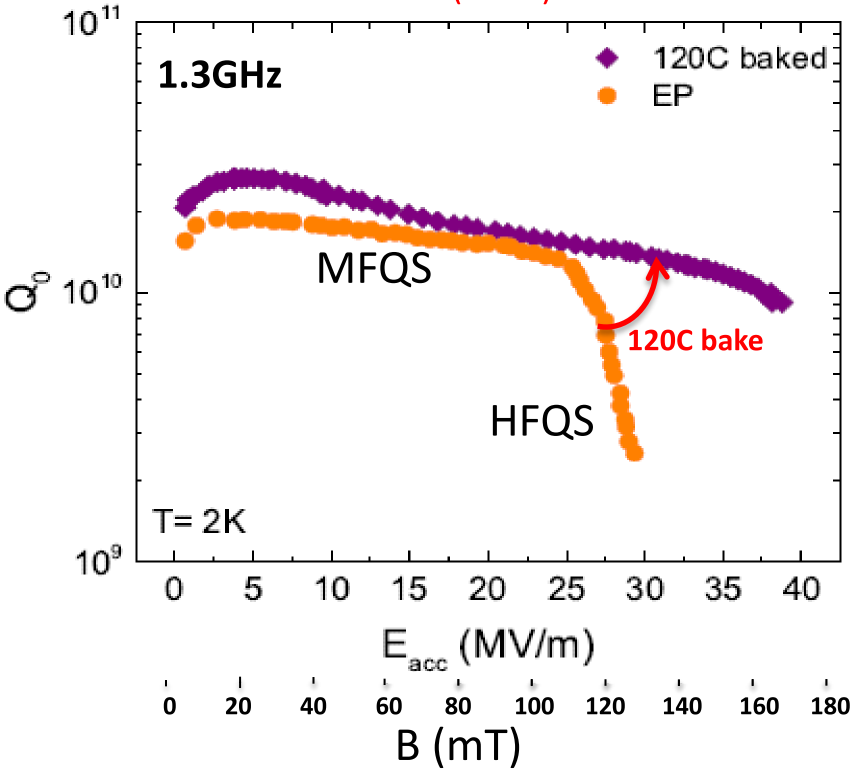
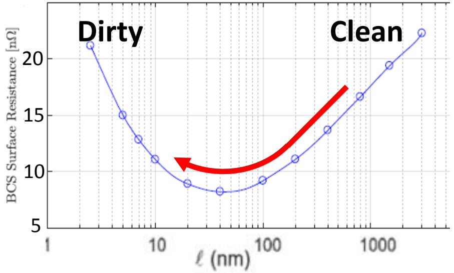


Global Baseline – 120 C Bake

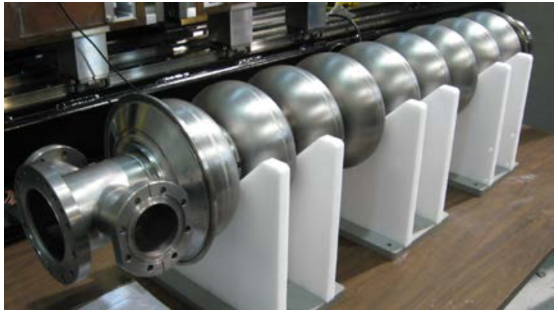
- Bake in vacuum at 120C for 48 hours mitigates high field Q-slope (HFQS) in 1.3GHz cavities
- Bake manipulates the surface oxide layer
  - Reduces the mean free path (dirtier) in the first 20-50nm to reduce the R_{BCS}
  - reduces lossy nano-hydrides
- Any cavity operating with $R_{BCS}>R_0$ can typically benefit from 120C bake

M. Martinello (FNAL) - Thesis





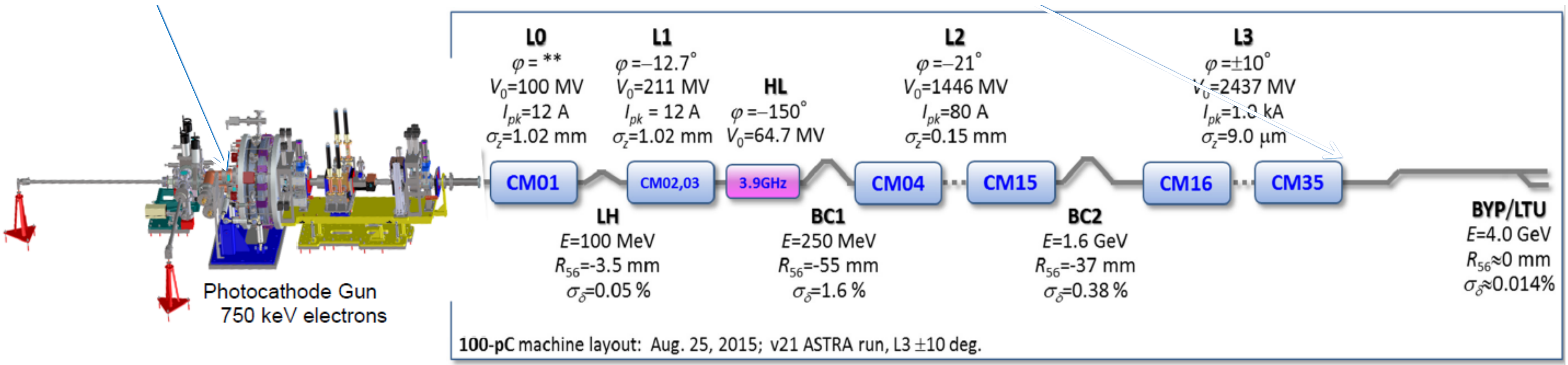
Recent Progress with Elliptical cavities



High Q – LCLS-II

- LCLS-II consists of 35 cryomodules each with 8 cavities – total of 280 cavities at 1.3GHz
- LCLS-II (boldly) chose N-doping as the baseline recipe with a cavity performance specification of:

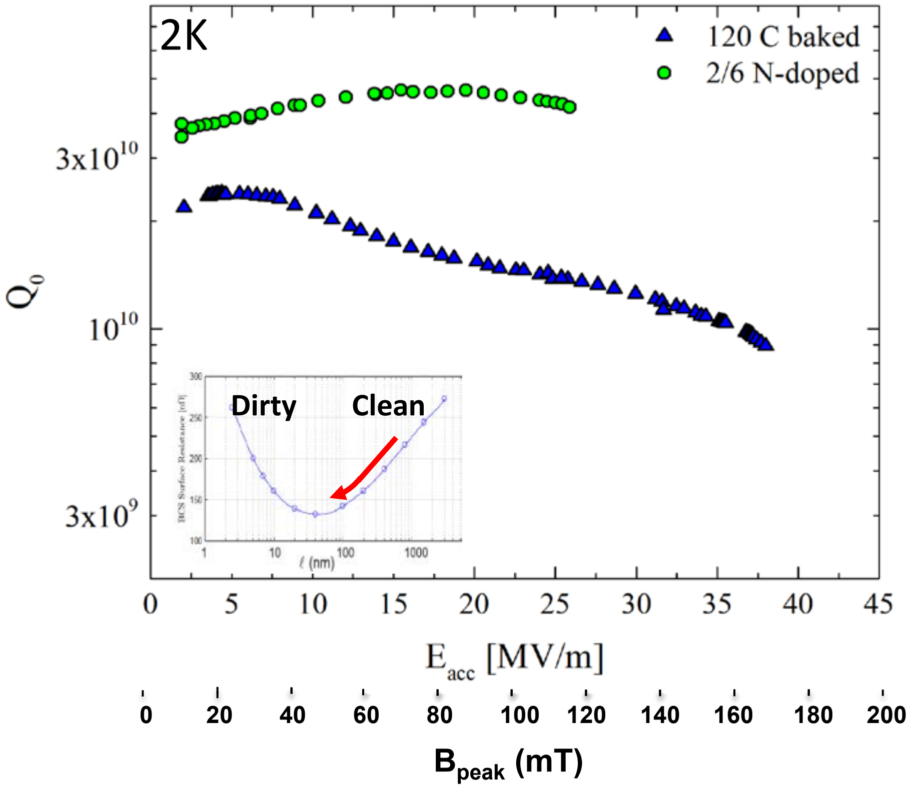
2.7 x 10^{10} at 16 MV/m and 2 K



Nitrogen Doping

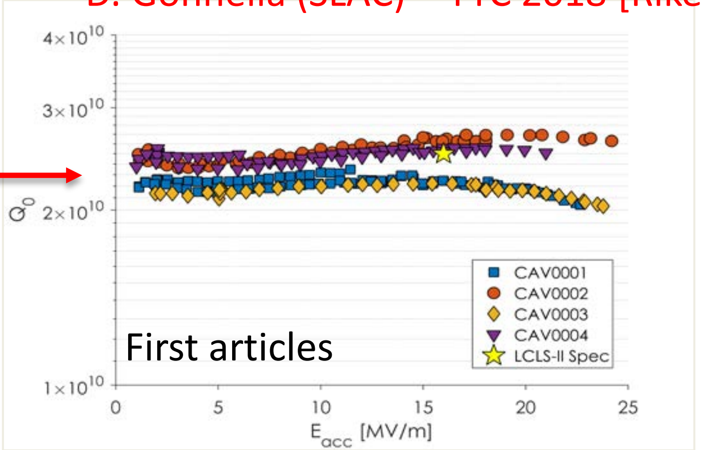
- N2 is introduced at 25 mTorr after 800C degassing for a few minutes
- N2 doping increases Q substantially by reducing electron mean free path, reducing BCS resistance with signature anti-Q-slope
- Requires 5-10 micron EP to clean the surface
- Results in a lower quench field and increased sensitivity to flux trapping

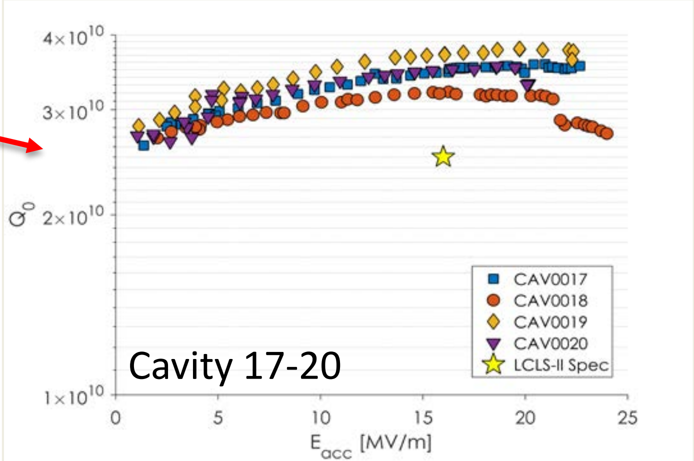
A.Grassellino, et al, Supercond. Sci. Technol. 26, 102001 (2013)



D. Gonnella (SLAC) – TTC 2018 [Riken]

- First articles from vendors did not perform as well as qualifying cavities – problem trapped flux -> rf losses
- It was found that different batches of material (that meet specification) can behave differently with respect to flux expulsion
- New treatment and processes developed to mitigate the issue – process now robust





Magnetic Flux Expulsion

Magnetic Flux Trapping

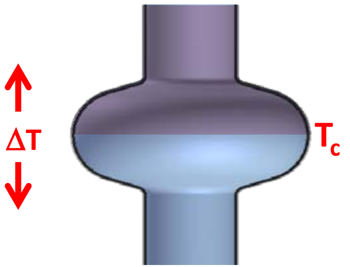
Obtaining and preserving Q ≥ 2.7e10 at 16 MV/m, 2K

$$R_S = R_{BCS} + R_0 + R_{TF} \le 10n\Omega$$

Doping — Intrinsic residual — Trapped flux resistance

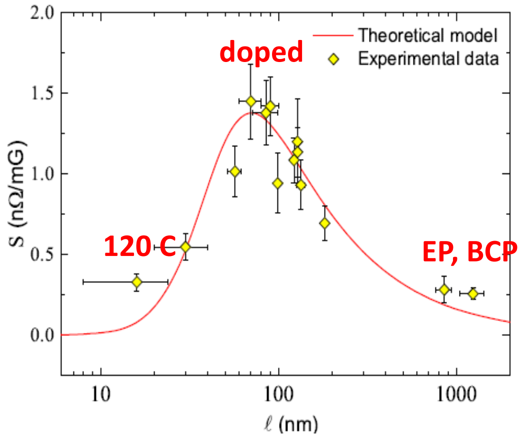
$$R_{TF} = S * \eta * B_{res}$$

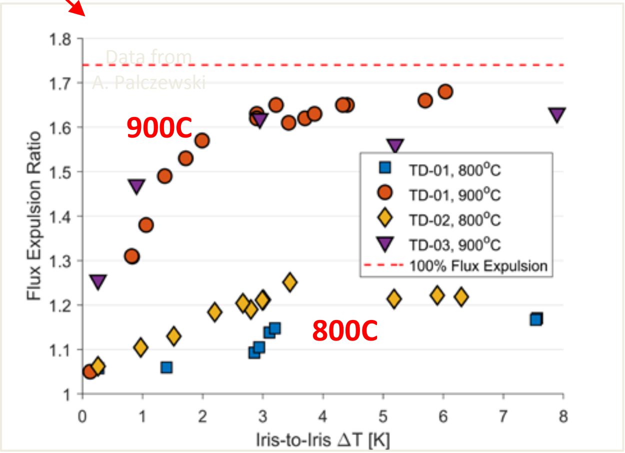
Sensitivity to trapped flux — Flux trapping percentage — Residual field



Study led to three important conclusions

1. Different treatments impact the sensitivity to trapped flux
2. Trapping percentage impacted by speed of cooldown
3. Trapping percentage impacted by material – heat treatments >800C help mitigate by reducing pinning





S. Posen et al., J. Appl. Phys. 119, 213903 (2016)

TTC 2018 [Milano] (M. Ross, SLAC)

S. Posen (FNAL) TTC [Milano]

FNAL utilizes new heat treatment and fast cooldown (>32 gm/s) to achieve 3.5e10 in the cryomodule

800C

Cavity	Usable Gradient* [MV/m]	Q0 @ 16 MV/m (or useable gradient) 2 K
CAV0008	20.5	2.0E+10
CAV0003	21.0	2.5E+10
CAV0006	21.0	2.0E+10
CAV0007	21.0	2.2E+10
CAV0016	18.2	1.8E+10
CAV0013	16.5	2.0E+10
CAV0011	20.5	2.3E+10
CAV0015	21.0	2.3E+10
Average	**20.0**	**2.1E+10**
Total Voltage	**166 MV**	

900C

Cavity	Usable Gradient* [MV/m]	Q0 @ 16 MV/m (or useable gradient) 2 K
CAV0034	21.0	3.4E+10
CAV0039	21.0	4.2E+10
CAV0040	10.0	3.6E+10
CAV0026	9.2	3.2E+10
CAV0027	21.0	3.2E+10
CAV0029	21.0	4.4E+10
CAV0042	16.8	2.8E+10
CAV0032	21.0	3.0E+10
Average	**17.6**	**3.5E+10**
Total Voltage	**146 MV**	

Fermilab CM-2
Cavities treated with baseline recipe

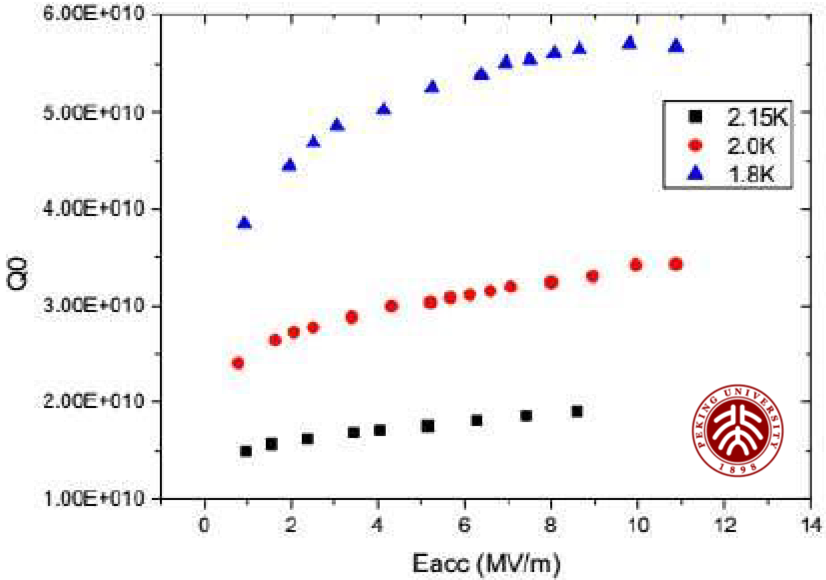
Fermilab CM-3
Treatment modified to improve flux expulsion

Total voltage Spec: 133 MV Q_0 Spec: 2.7×10^{10}

1.3GHz N-doping Summary

- LCLS-II
  - High Q_0 has been reliably demonstrated after early pains - Q_0 more than 3.4×10^{10} can be consistently achieved
- Conclusion:
  - Nitrogen-doping is a robust reproducible procedure
  - Flux expulsion is the most important factor limiting performance
  - Low residual field and fast cooldown are required to get the best performance
  - Flux expulsion is material dependent – heat treatments can help – community engaged with vendors to optimize

Dong Wang TTC2018 [Milano]

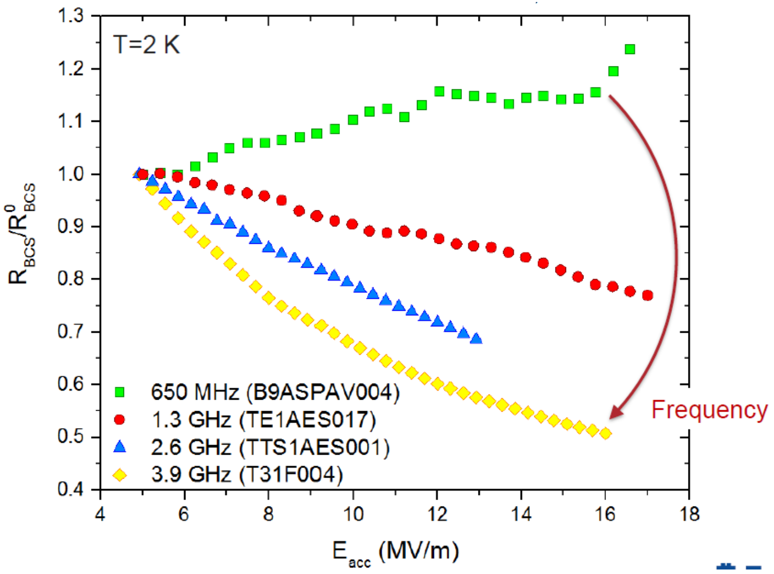


PKU N-doped 1.3GHz cavity

Doping and Frequency Dependence

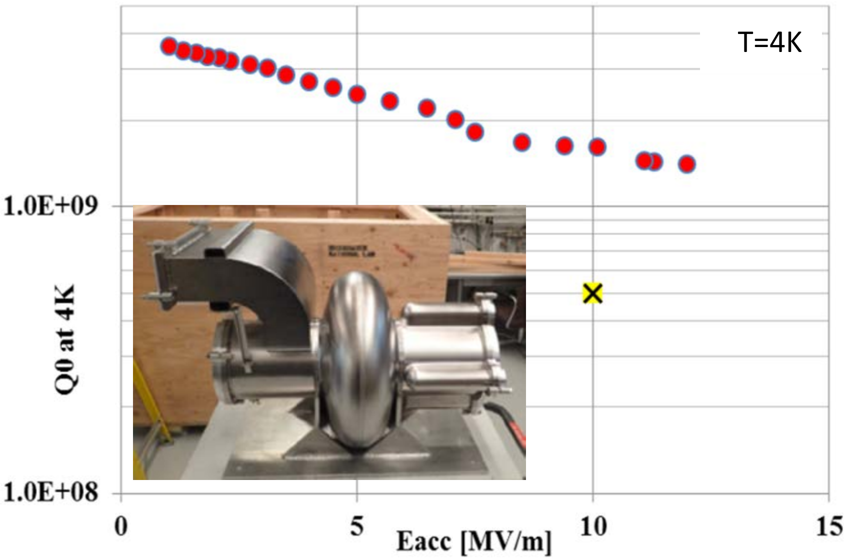
N-doping favours higher frequency 2K applications

FNAL data: negative Q-slope at 2K would be expected for freq>1GHz



M. Martinello (FNAL) SRF 2017 [Lanzhou]

Cornell achieves factor of 2 gain in Q at 500MHz and 4K with N-dope



F. Furuta†(Cornell) IPAC2018 [Vancouver]

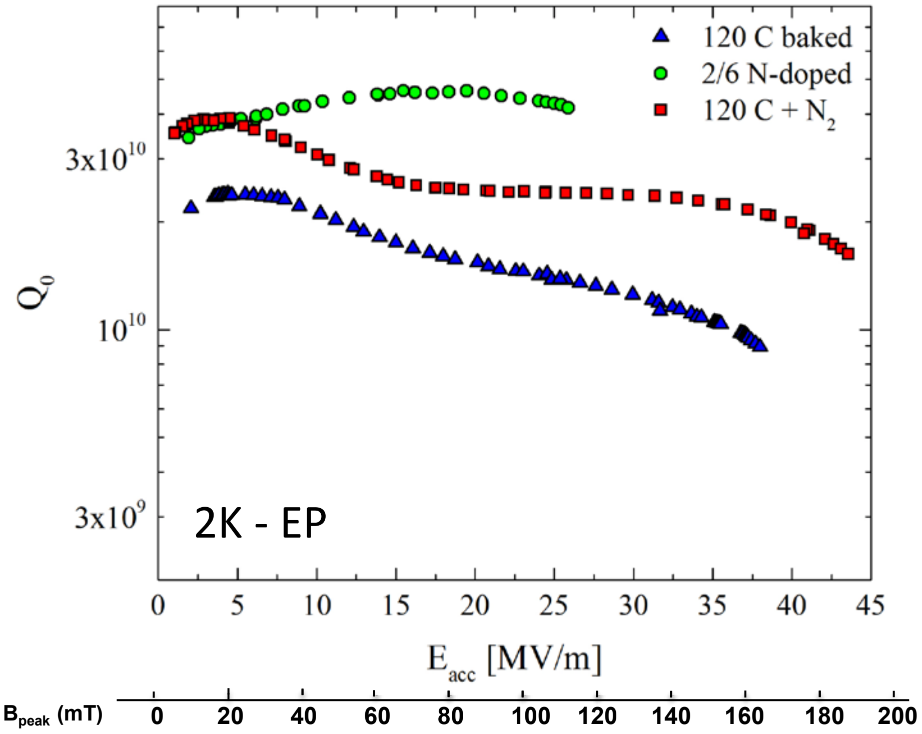
High Q, High Gradient

Nitrogen Infusion

- After 800◦C degas, the temperature in the furnace is lowered to 120-160◦C (under vacuum), 25mTorr nitrogen is introduced for 48h.
- The N2 infusion treatment (FNAL) raises Q and extends gradient beyond standard 120C recipe
- No chemistry after treatment.
- **Potential treatment for ILC**

A. Grassellino,et al, Supercond. Sci. Technol. 30, 094004 (2017).

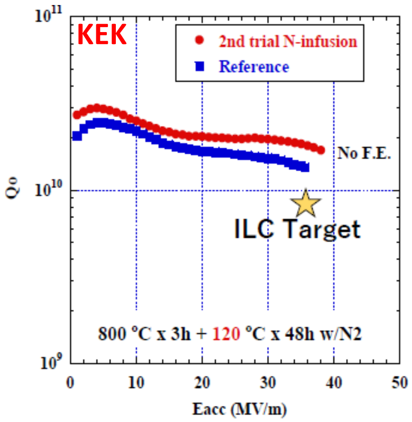
A. Grassellino (FNAL) – TTC 2016 [Saclay]

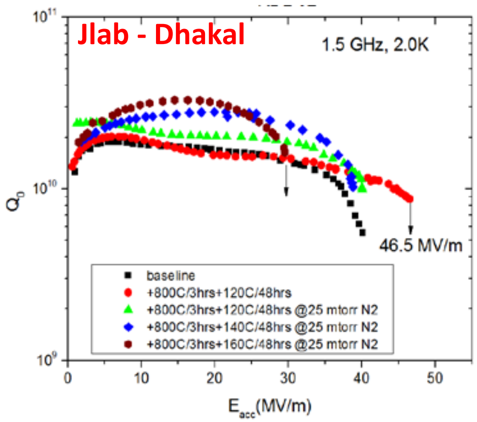


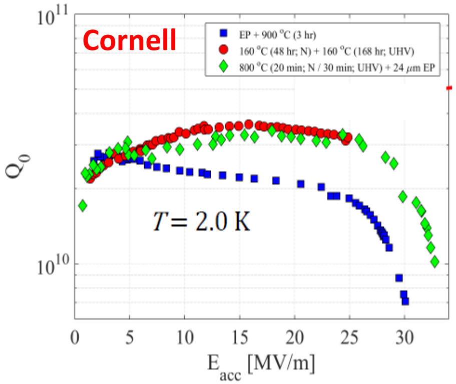
KEK

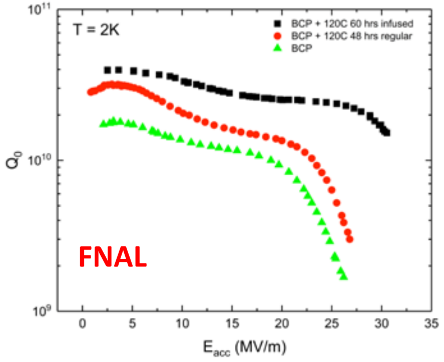
Infusion Experience Worldwide

- This has proven to be a challenging recipe – very dependent on the quality of the vacuum furnace
- N-Infusion research is on-going at a number of SRF centers worldwide
- KEK – successful at 20% of attempts
- J-Lab – Cornell - higher Q but not gradient - Cornell – experimenting with N and other dopants - C and O
    - Infusion vs doping – no need for post chemistry with infusion
- FNAL – succeeded with infusion on BCP cavities







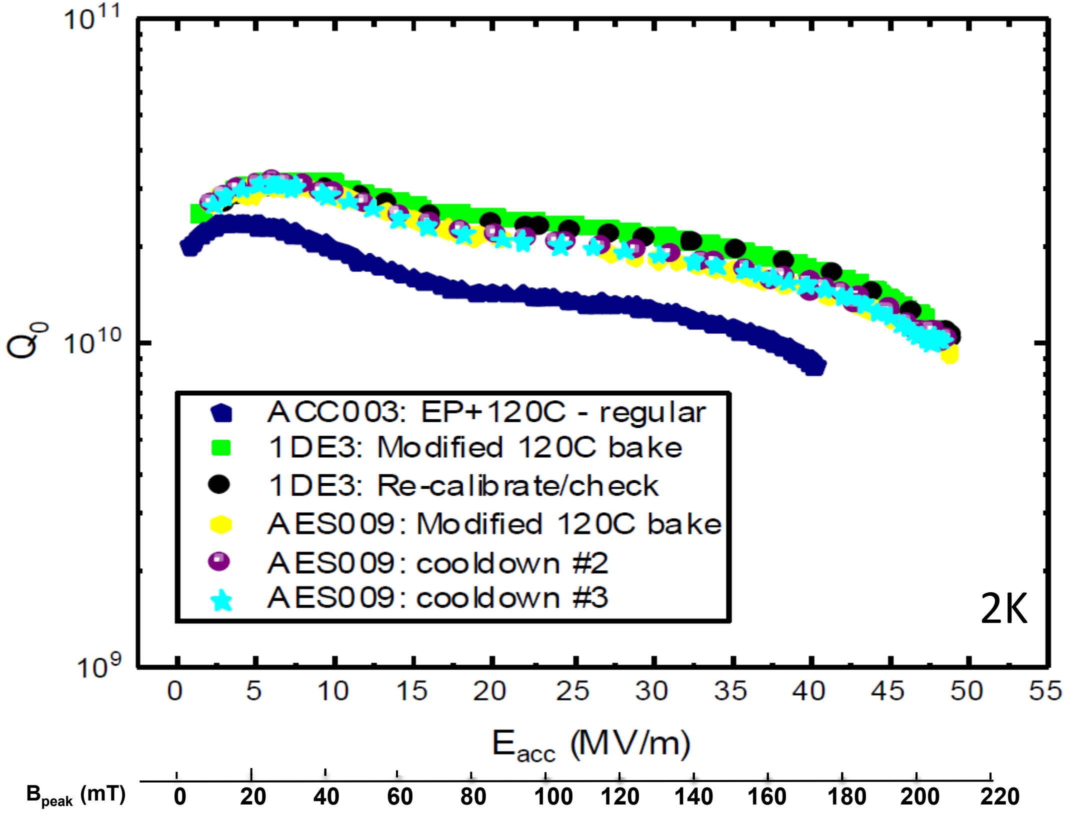


See Marc Wenscat TH2A01

Low temperature (Magic) Recipe

- New recipe from FNAL - raises Q and extends the reachable field beyond standard 120C recipe
- Standard 120C bake but with an initial hold at 75C for 3 hours
- No nitrogen required!
- No chemistry required!
- This will undoubtedly double efforts to try to harness the optimum high Q, high gradient recipe

A. Grassellino (FNAL) – TTC 2018 [Riken]



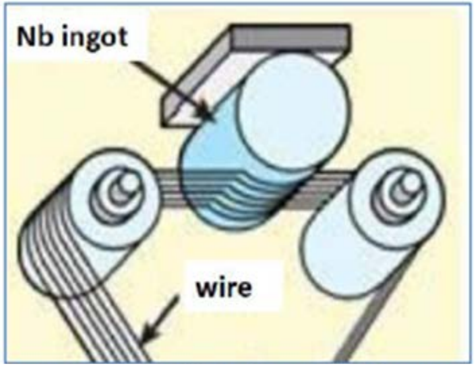
Fine grain vs large grain

Large Grain Niobium from Ingot

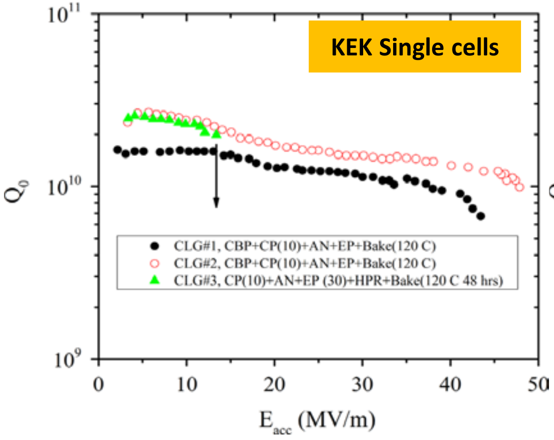
P. Dhakal (Jlab) TTC2018 [Riken]

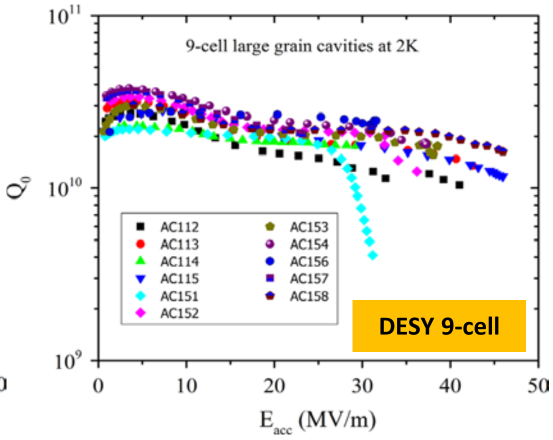
- Lower material cost – less steps
- Need to optimize processing and demonstrate forming technique for industrial production
- Sheet production by slicing may be less prone to `pinning' variations seen in LCLS-II material
- DESY and KEK show impressive high field performance - near 50MV/m and Q=1e10

Large grain Nb sheet

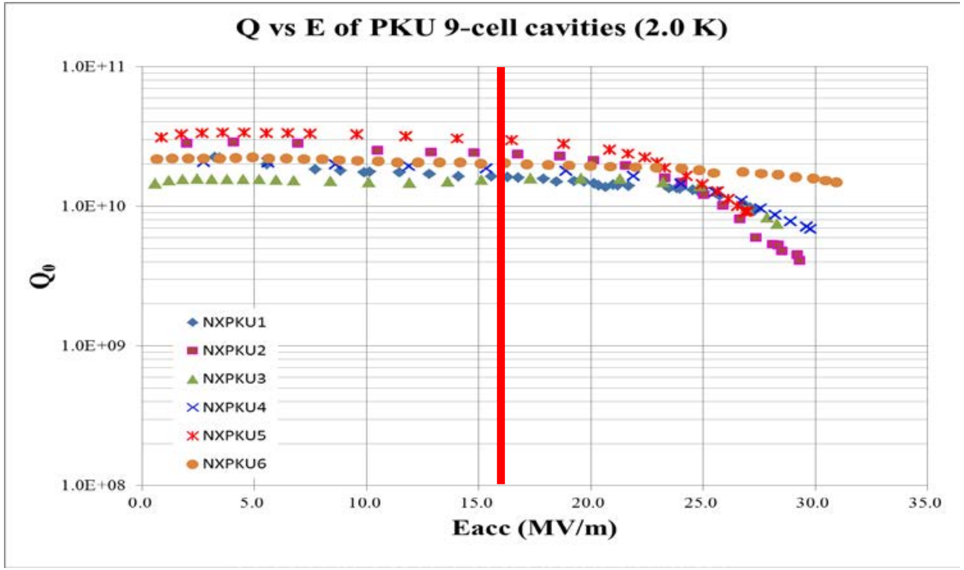


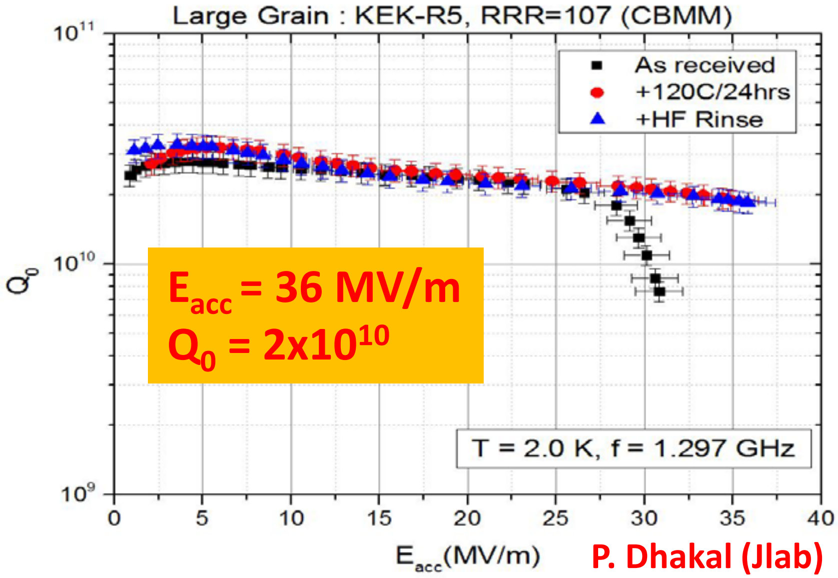
Direct slicing from Nb ingot





LARGE GRAIN CAVITIES





P. Dhakal (Jlab)

- 6 large grain 9-cell cavities were fabricated and post-treated in PKU
- Only BCP, no EP
- Vertical tested in 2017 at PKU
- E_{acc} of 6 cavities all larger than 25 MV/m

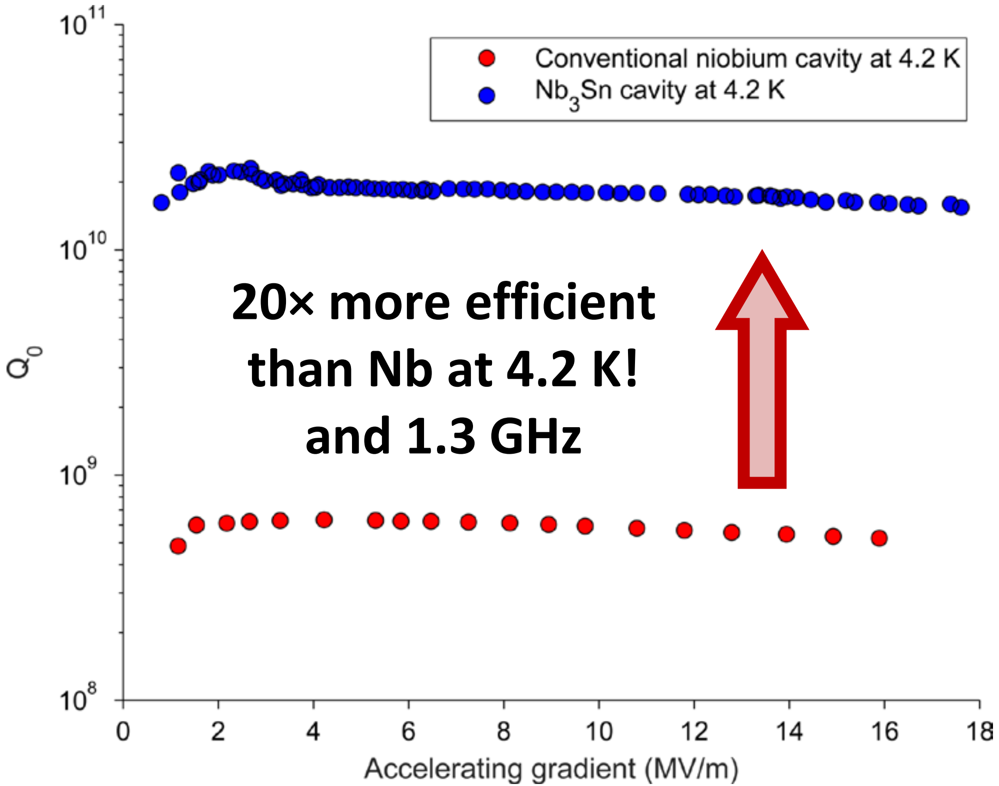
A Large grain cavity (ingot from CBMM) fabricated and processed at KEK was tested at JLAB - measured record Q and gradient for RRR= 107.

E_{acc} = 36 MV/m, $Q_0 = 2x10^{10}$

Beyond Bulk Niobium

Nb_3Sn Development

M. Liepe (Cornell)

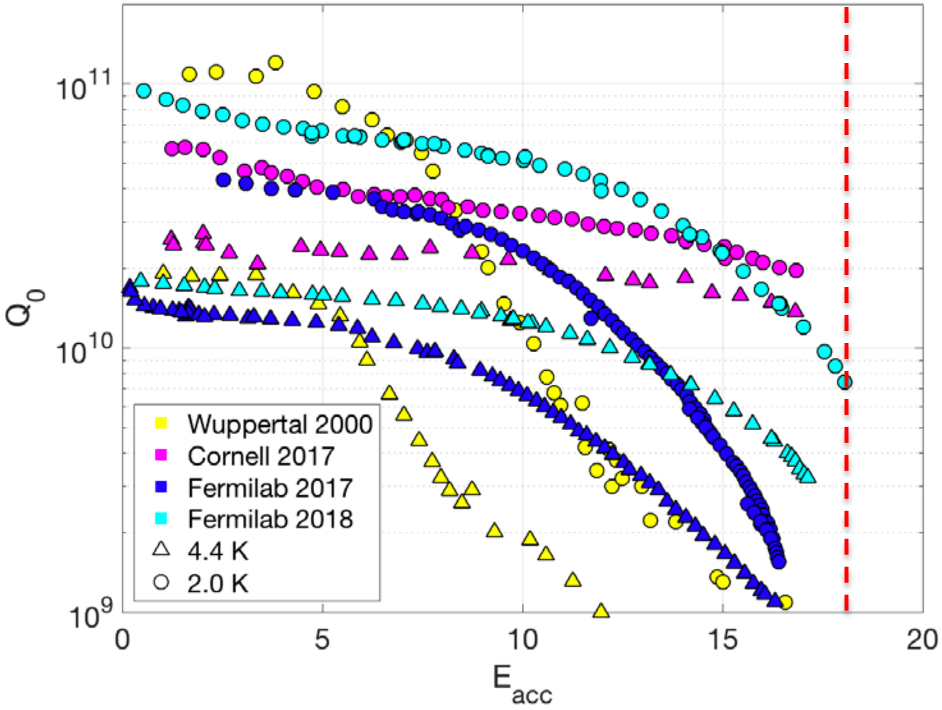


- Why Nb_3Sn?
  - Nb3Sn still remains the only new material that has produced a result suitable for acceleration
  - **High H_{sh}** means high theoretical max accelerating gradient (~ 96 MV/m)
  - **1.3GHz at 4.2 K** means cheaper cryogenics!
- Current State:
  - **18 MV/m CW** operation
  - **26 MV/m pulsed** operation
  - High Q of **2×10^{10}** at 4.2 K operation

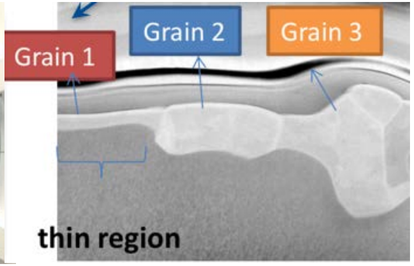
Nb3Sn Development

- Work continues globally to optimize the coating – Focus is on understanding limitations in the film - defects and tin depleted regions
- FNAL is extending applications to nine cell and 650MHz
- What is limiting gradients to 18MV/m at 1.3GHz - a fundamental limit?

S. Posen (FNAL) – TTC 2018 [Riken]



FNAL furnace

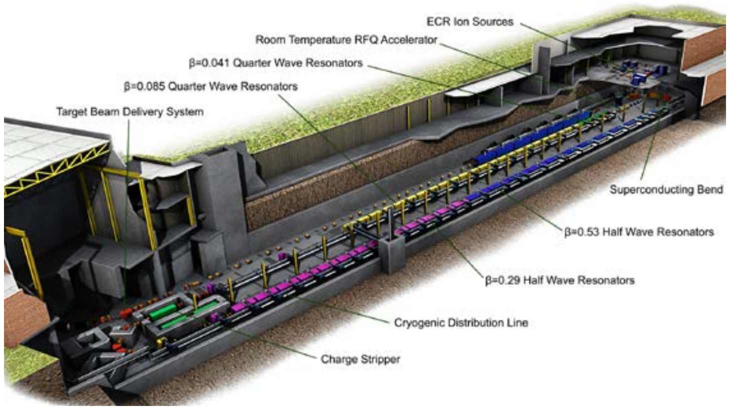


FNAL sample

Non-elliptical Cavities

FRIB Heavy Ion Linac

- FRIB is the largest SC hadron linac ever built
- Cavity fabrication almost complete – CMs at 50%
- Technical highlights
  - CM performance is matching vertical test – for all four cavity variants
  - Beam test of first 3 CMs very successful

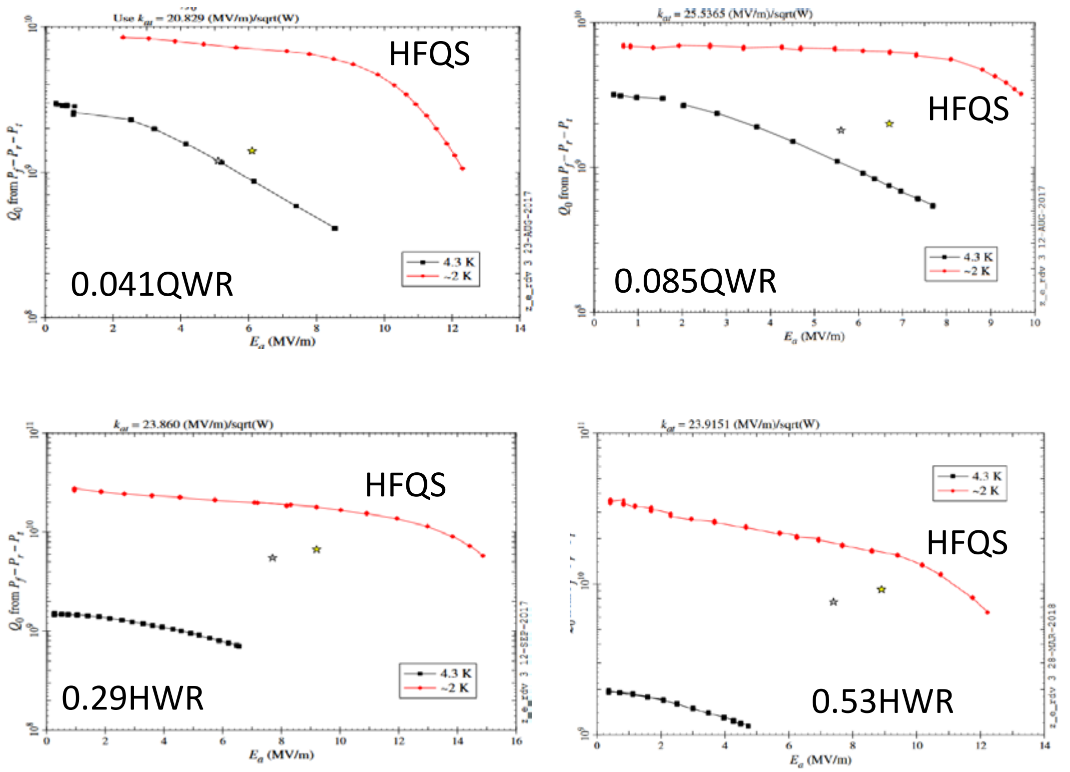


See E. Pozdeyev WE2A01

Cavity beta	# required	# received	Certified	CM required	CM built
QWR 0.041	16	16	16	3	4
QWR 0.085	92	123	101	11	11
HWR 0.29	72	83	72	12	7
HWR 0.53	147	118	101	18	2
Totals	**327**	**340**	**290**	**44**	**24**

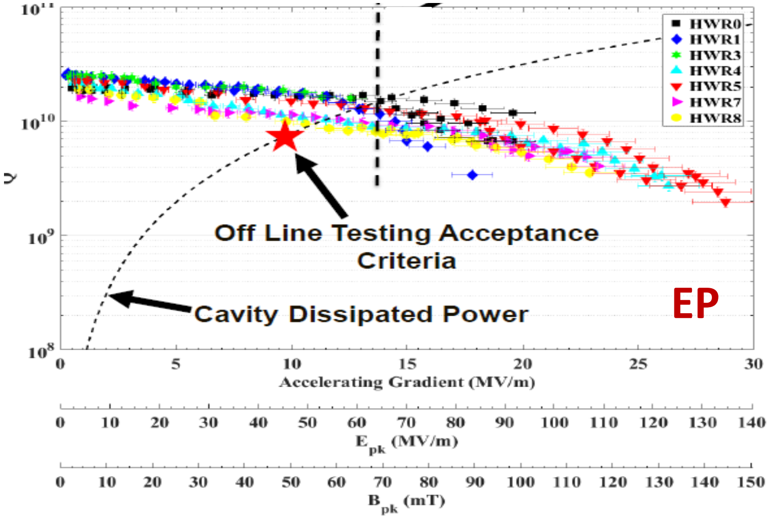
K. Saito (FRIB) TTC2018 [Riken]

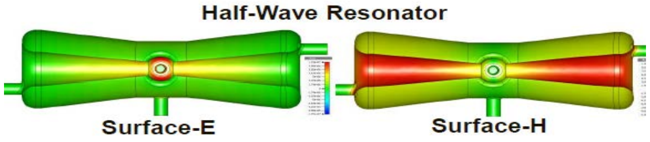
- FRIB offers rich data set
- High field Q-slope (HFQS) without X-ray is observed in each cavity family.
- The average onset field is coincident at a **Bp ~ 85 mT** corresponds to Eacc=20MV/m for ILC cavity – similar to the onset field of HFQS with BCP'ed cavities.
- **Could high field performance be improved with EP?**



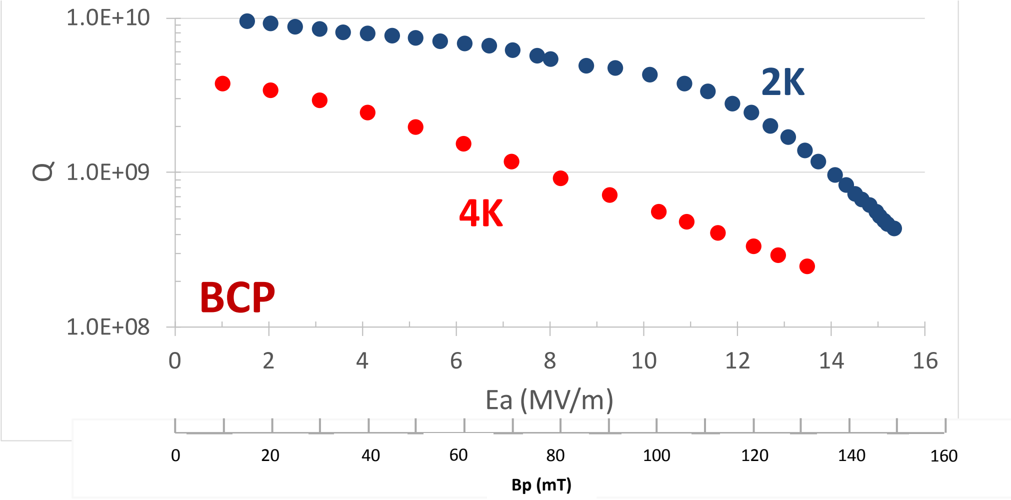
Performances are continuing to improve – latest results from ANL and TRIUMF (RISP) indicate cavities operating at up to **Bp~143mT** for both EP and BCP cavities respectively with ANL at **Ep=135MV/m**! (well above beta=1 cavity)

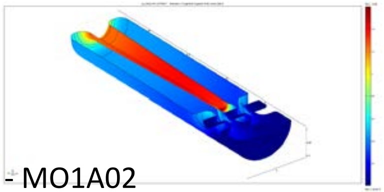
ANL HWR Performance





RISP QWR Tested at TRIUMF

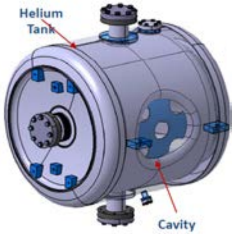


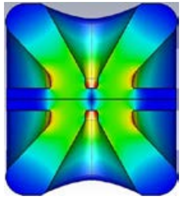


IPNO Developments

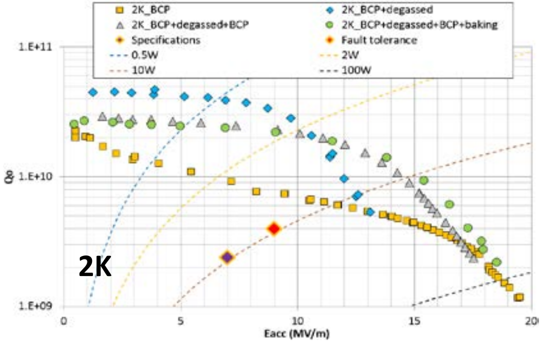
D. Longuevergne (IPNO)

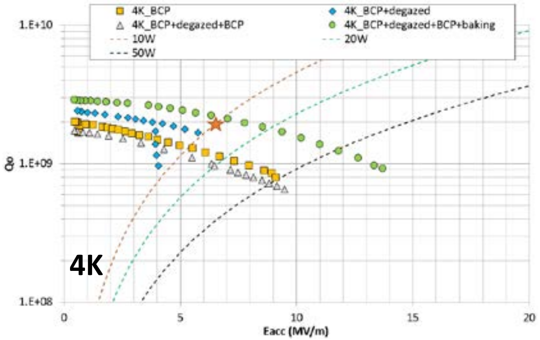
- Excellent developments with 352 MHz spoke resonators for ESS and Myrte – reach **Bp=140mT**
- Concentrating on heat treatments and post-processing – find that using Nb caps during degassing cycle can eliminate the need for final chemical etch – better Q achieved – $\mathbf{R_0=1.3n\Omega}$!
- Also studying flux expulsion as a function of geometry – QWR vs SSR vs DSR





Cavities are degassed at 650°C during 10h with their titanium tank with Nb caps to reduce contamination





New Cavity Variants

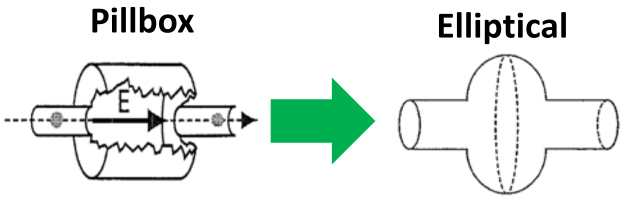
SSR Balloon Resonator

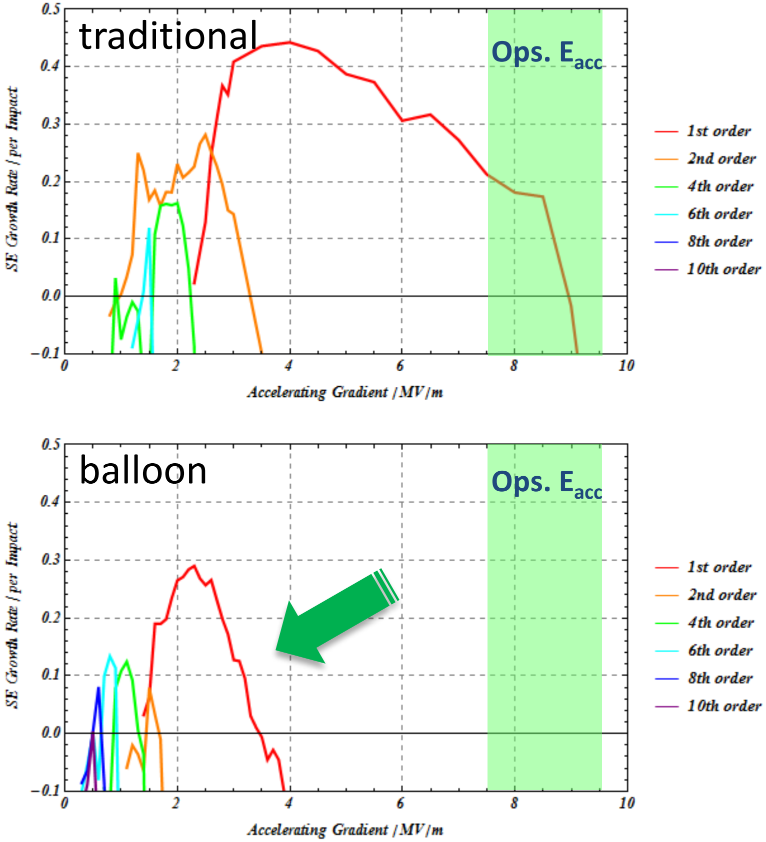
See Z. Yao TUOP07

TRIUMF has developed a new variant of the Single Spoke Resonator called the balloon cavity

- Eliminate multipacting at high field
- Mechanically more stable – drum vs sphere

The development recalls the evolution from pill box to elliptical cavity in the early days of SRF to reduce the impact of multi-pacting

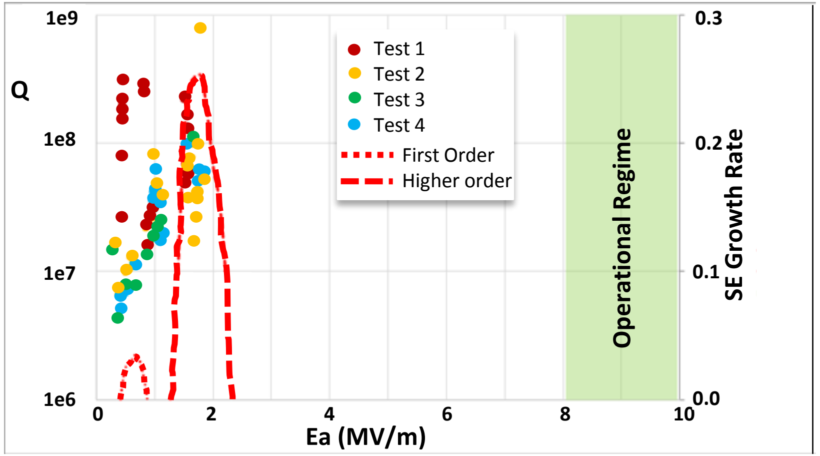


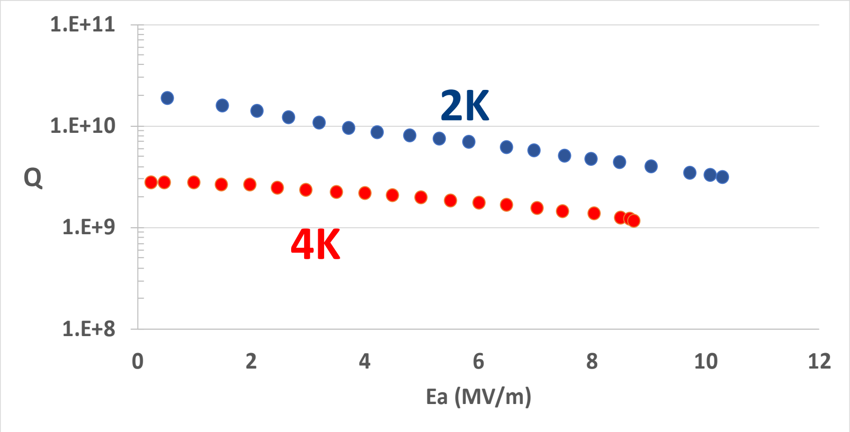


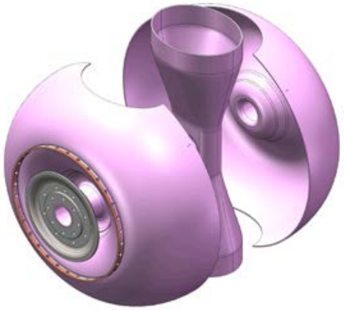
Multipacting simulations confirmed in First Balloon Cold Test

TRIUMF: First demonstration of Balloon geometry 325MHz β=0.3

- There is excellent agreement between MP simulations and cold test data
- No multipacting barriers near the operational gradient or below 0.1 MV/m.
- Designed and fabricated by TRIUMF for RISP project



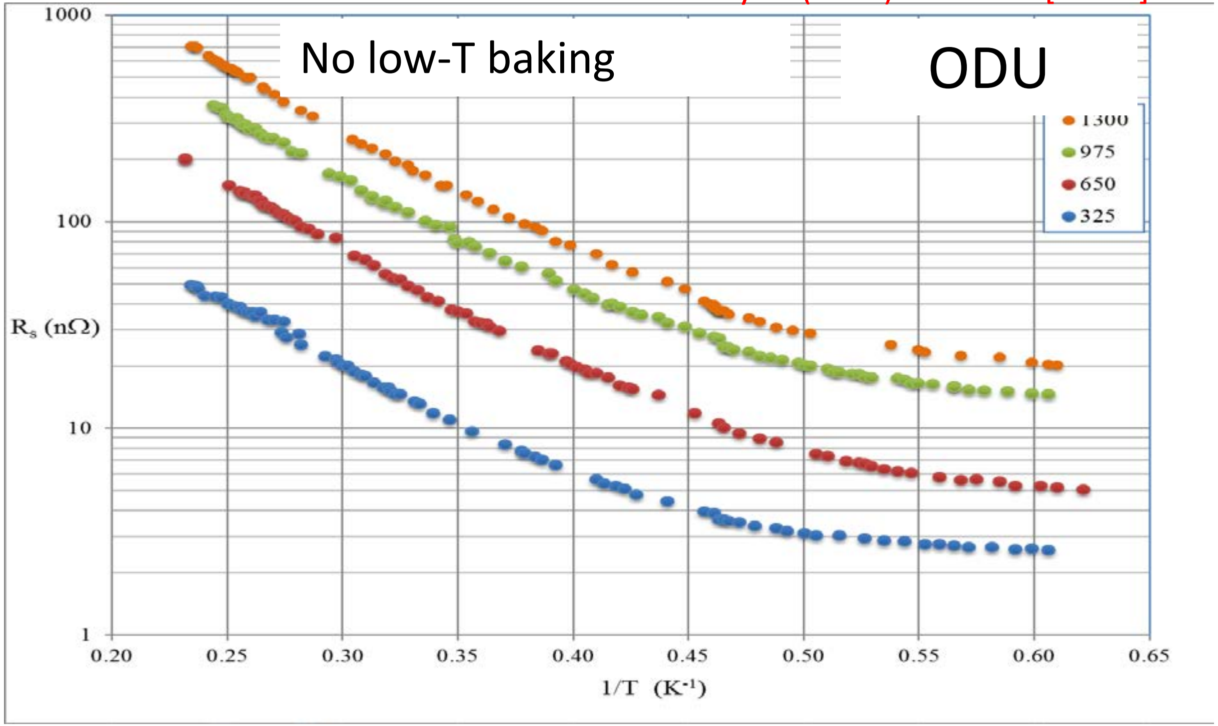


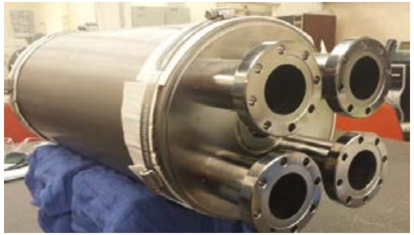


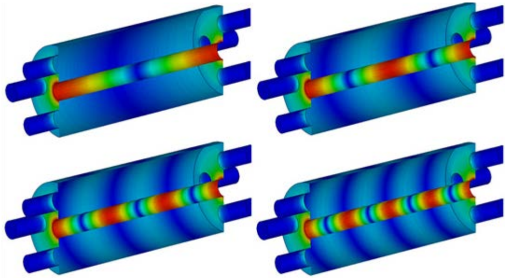
Coaxial Resonators for Frequency Dependence Study

ODU has fabricated and tested a coaxial HWR for fundamental SRF studies – goal is to study frequency dependent surface resistant in the same cavity using fundamental and harmonics in the same cold test.

Delayen (ODU) TTC2018 [Riken]



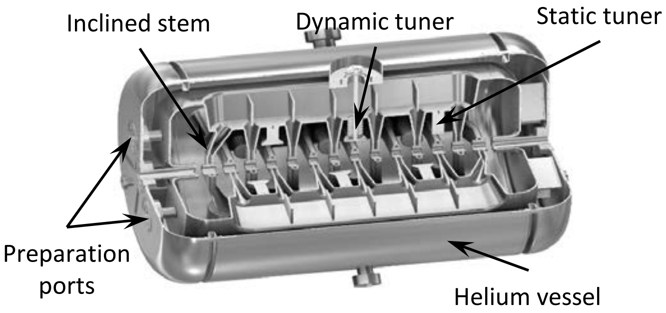




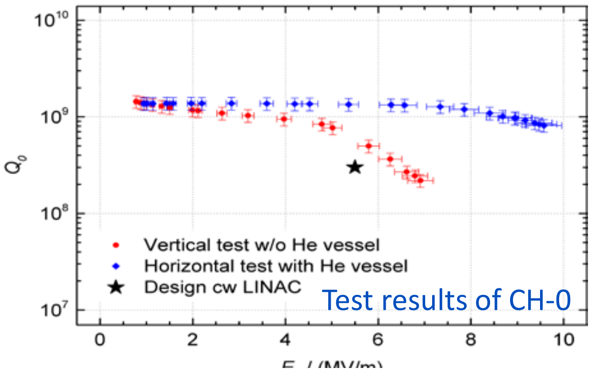
See H. Park TUOP04

CW-Linac based on 217 MHz sc CH-cavities - CH-0 successfully demonstrated first acceleration

See W.A. Barth TU2A01

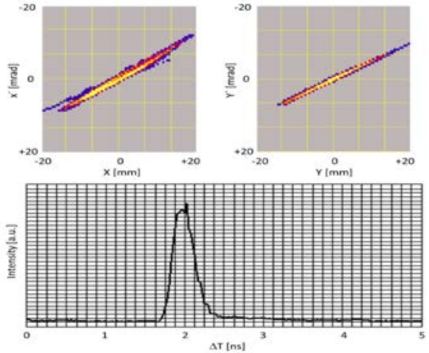


217 MHz Demonstrator cavity CH-0



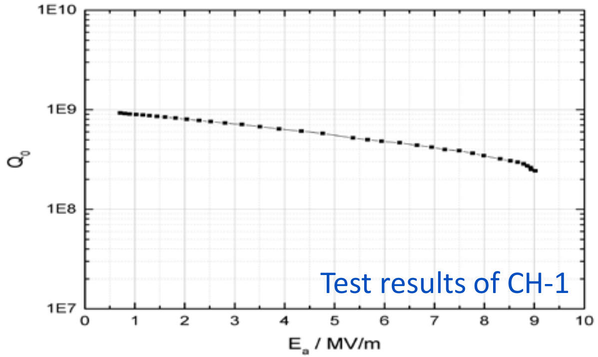
Test results of CH-0

CH-0



Successful beam test at GSI with CH-0 with up to 6 MV/m

W. Barth et al., PRAB ***21****, 020102 (2018)*



Test results of CH-1

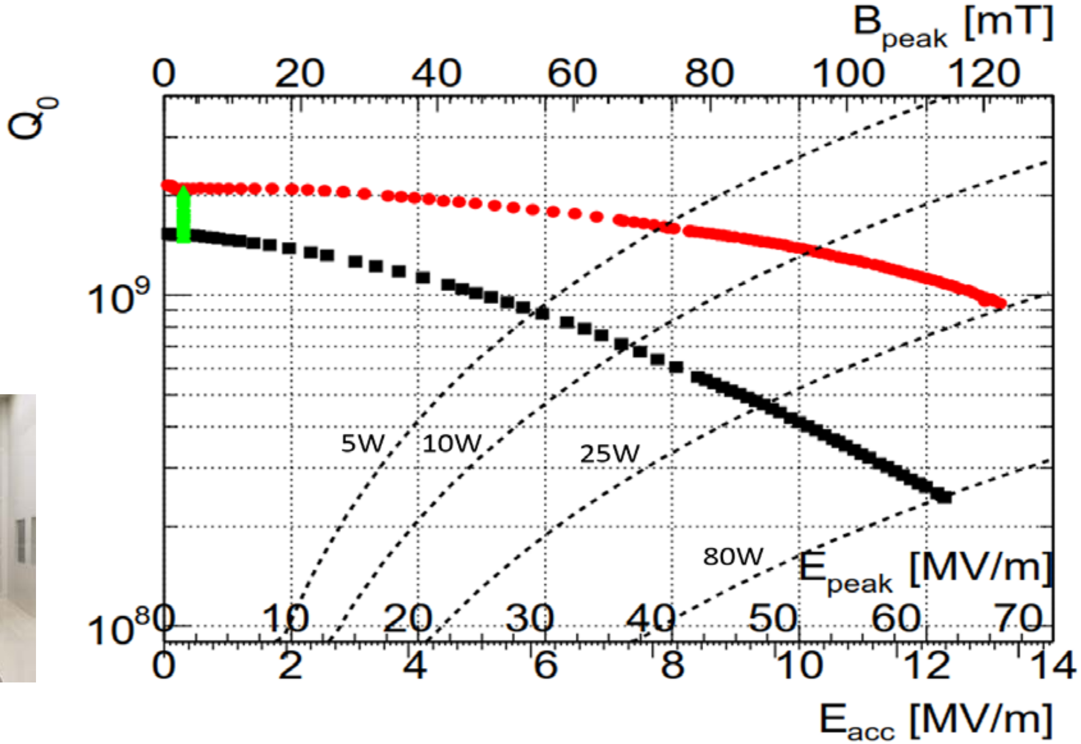
CH-1

Collaboration between GSI, Helmholtz Institut Mainz, University Mainz, University Frankfurt

Technology Developments

See W. Venturini Delsolaro TU1A05

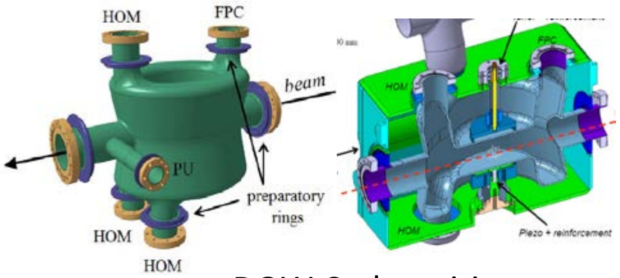
- HIE-Isolde now has installed three cryomodules of QWR sputtered Nb on Cu cavities
- Seamless QWR reached unprecedented peak fields for Nb/Cu



W. Venturini Delsolaro (CERN),

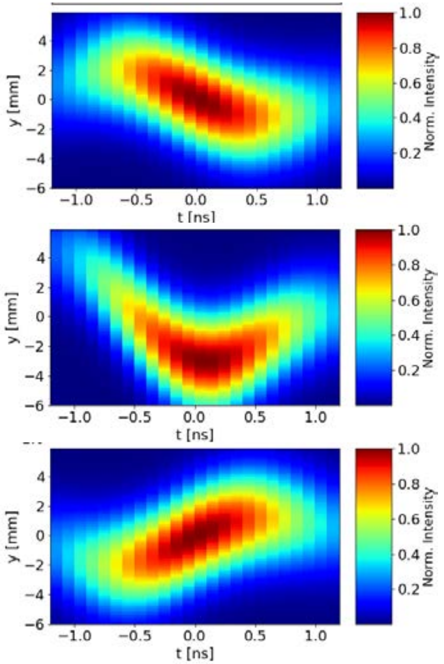
IMP is also looking now at Nb on Cu for C-ADS development

Double quarter wave (DQW) have been fabricated and assembled into a cryomodule for a proof of principle beam test in CERN SPS



DQW Crab cavities

First crabbing of a proton beam



0 Deg

90 Deg

180 Deg

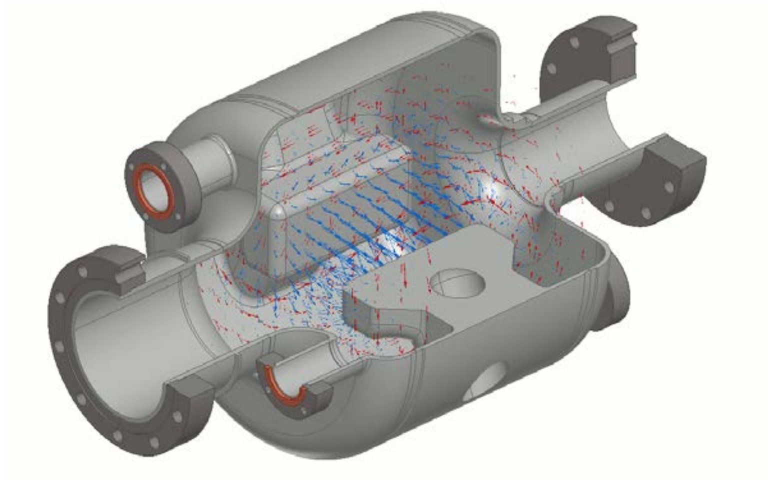
Cavity string assembly

DQW cryomodule installed in the SPS

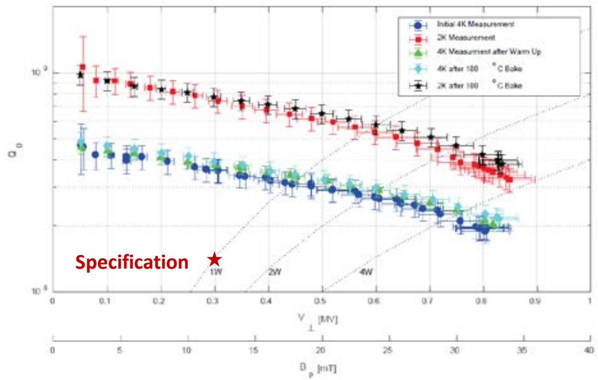
R. Calaga, O. Capatina, F. Gerigk, A. Macpherson, M. Therasse, G. Vandoni

SRF Dipole Cavity – Low cost manufacture

- 650MHz rf deflecting mode cavity has been fabricated from reactor grade Niobium machined from bulk and with TIG welding
- First superconducting rf cavity fabricated at TRIUMF
- Cavity recently tested and meets design specification



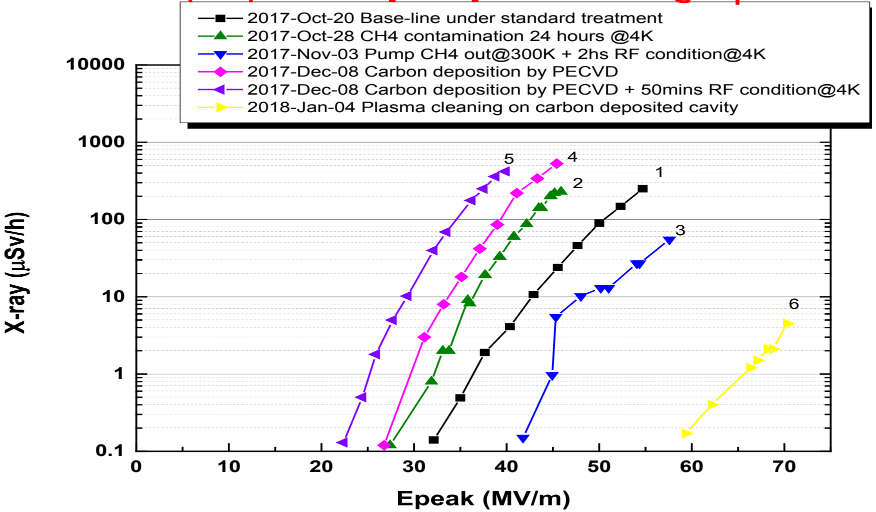
Separator Cavity 4K and 2K Test Results



Plasma cleaning on TEM Mode Cavities

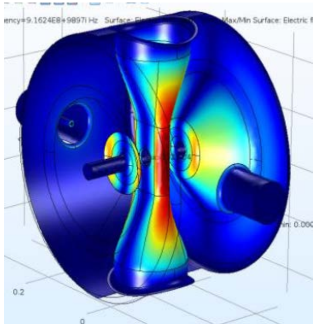
- IMP plasma cleaning on HWR
  - Max E_{peaks} increased from 57MV/m to 70MV/m (23%) after plasma cleaning
  - Onset of the FE increased from 32MV/m to 58MV/m (43%)
  - MP effect eliminated at E_{peak}=16MV/m

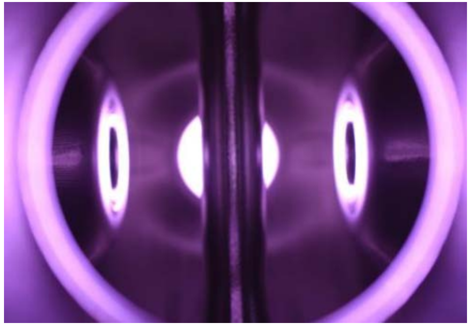
Y. He (IMP) TTC2018 [Riken] antonwoo@impcas.ac.cn



- FNAL plasma cleaning on SSR
  - Developing plasma cleaning for 9 cell 1.3GHz cavity – ignition with HOMs
  - Also developing plasma leaning of SSR cavity – Argon at 250mTorr 2-30W
  - Require correct mix of modes to cover areas of interest

P. Berrutti (FNAL) TTC2018 [Riken]

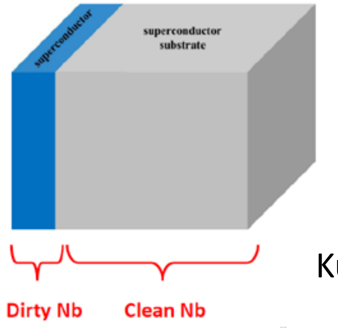




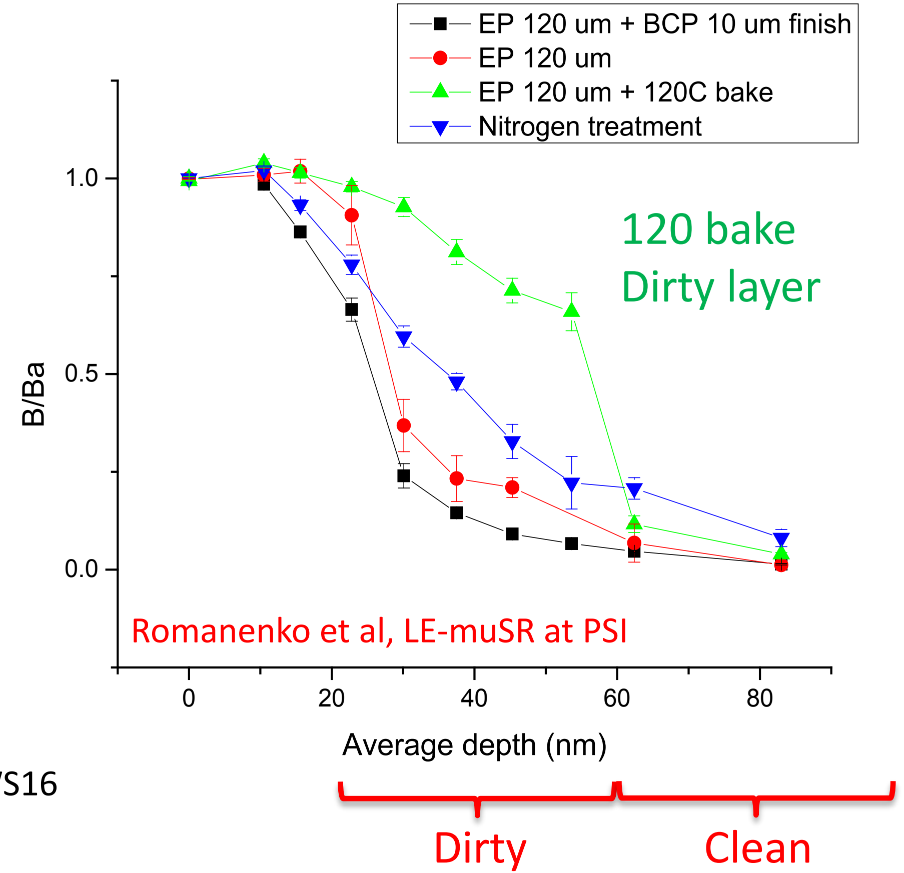
Where are we going?

A. Romanenko et al., Appl. Phys. Lett. **104**, 072601 (2014)

- 120C bake is known to manipulate the mean free path at the near surface creating a dirty layer of ~50nm
- A dirty layer seems beneficial in order to increase the quench field beyond B_{c1} - theoretical models agree
- N infusion and magic bake provide other means to create a dirty layer

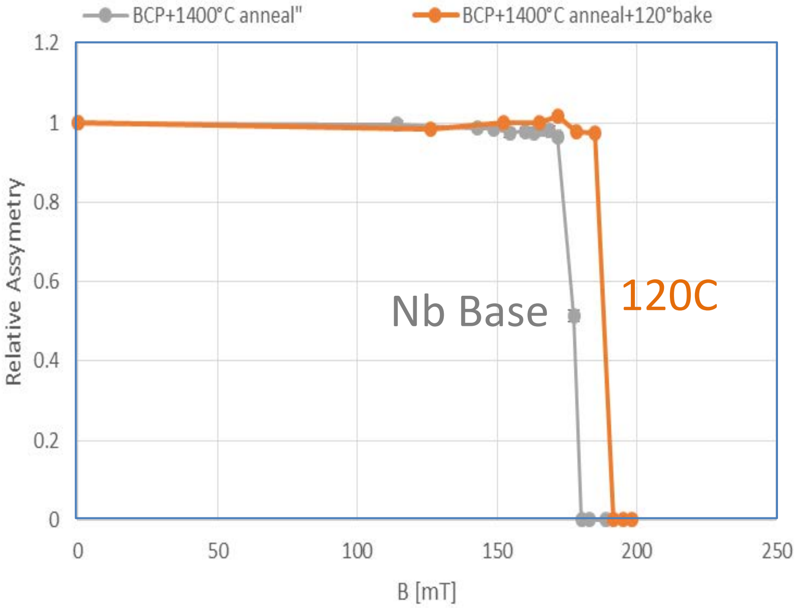


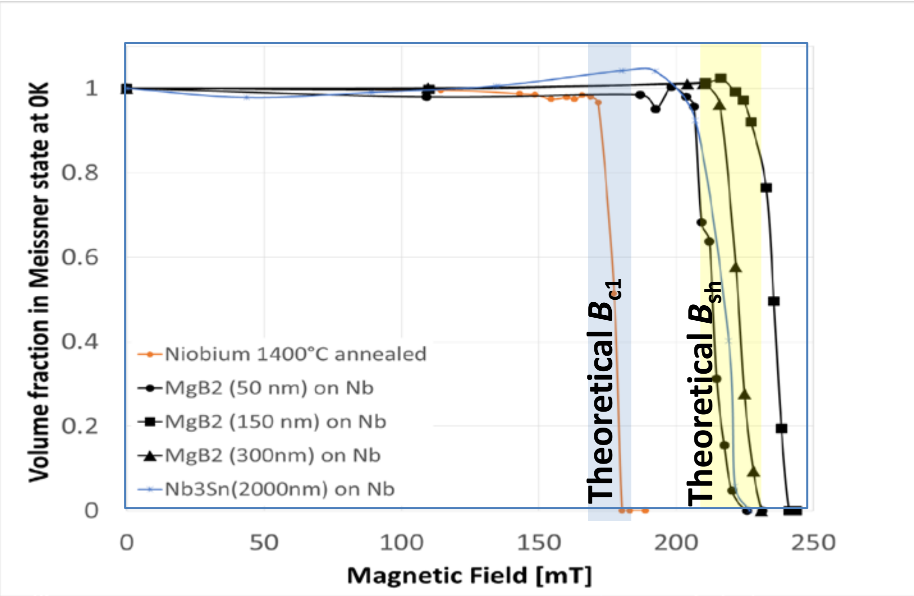
Kubo, LCWS16



muSR Findings (TRIUMF): *Baking at 120C (high K) enhances the field of first flux entry; A layer of a high K and Tc material on niobium enhances the field of first entry by about 40% .*

- Consistent with `dirty layer' hypothesis.



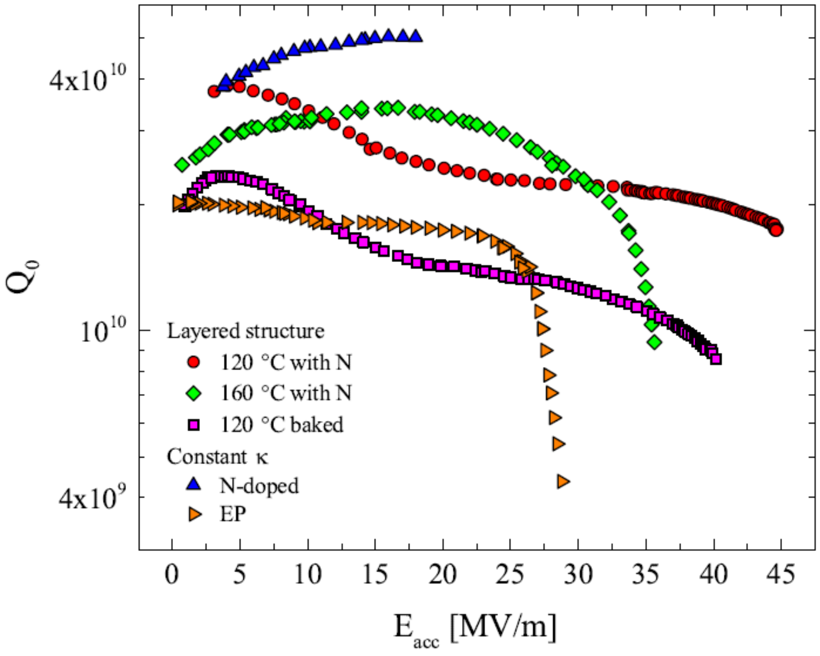


T. Junginger, R. Laxdal, W. Wasserman, *Superheating in coated niobium*, SUST, DOI: 10.1088/1361-6668/aa8e3a, 2017

Engineering a Dirty Layer

- ILC and other projects are looking for reproducible robust recipes that can be replicated in industry
- We know that variations in the dirty layer produce significant variations in performance
- Strategy: to engineer a surface layer on bulk Nb to reproducibly optimize the performance
- Thin film research and theory are continuing in parallel – Nb3Sn, SIS layers, high frequency cavities, ?
- Stay tuned!

Checchin (FNAL), thesis



Acknowledgements

Many thanks to my colleagues for providing the information:

P. Dhakal (Jlab), S. Posen (FNAL), M. Liepe (Cornell), D. Longuevergne (IPN-Orsay), C. Madec (Saclay), W. Venturini Delsolaro (CERN), K Umemori (KEK), H. Sakai (KEK), H. Podlech (IAP), K. Liu (PKU),
A. Grassellino (FNAL), D. Gonnella (SLAC), M. Martinella (FNAL), M. Checchin (FNAL), A. Romanenko (FNAL), F. Dziuba (IAP), T. Kubo (KEK,ODU), J. Delayen (ODU)

Apologies for the material I was not able to present!

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Thank you!
Merci!
谢谢

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