Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Recent SRF R&D results at Fermilab

Martina Martinello

FCC week 2018

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Outline

- Recent SRF R&D results at Fermilab:
  - High-Q at high gradients
  - Frequency dependence of the surface resistance
  - Nb_3Sn
- Technologies comparison for FCC-ee
- Conclusions

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- Recent SRF R&D results at Fermilab:
  - High-Q at high gradients
  - Frequency dependence of the surface resistance
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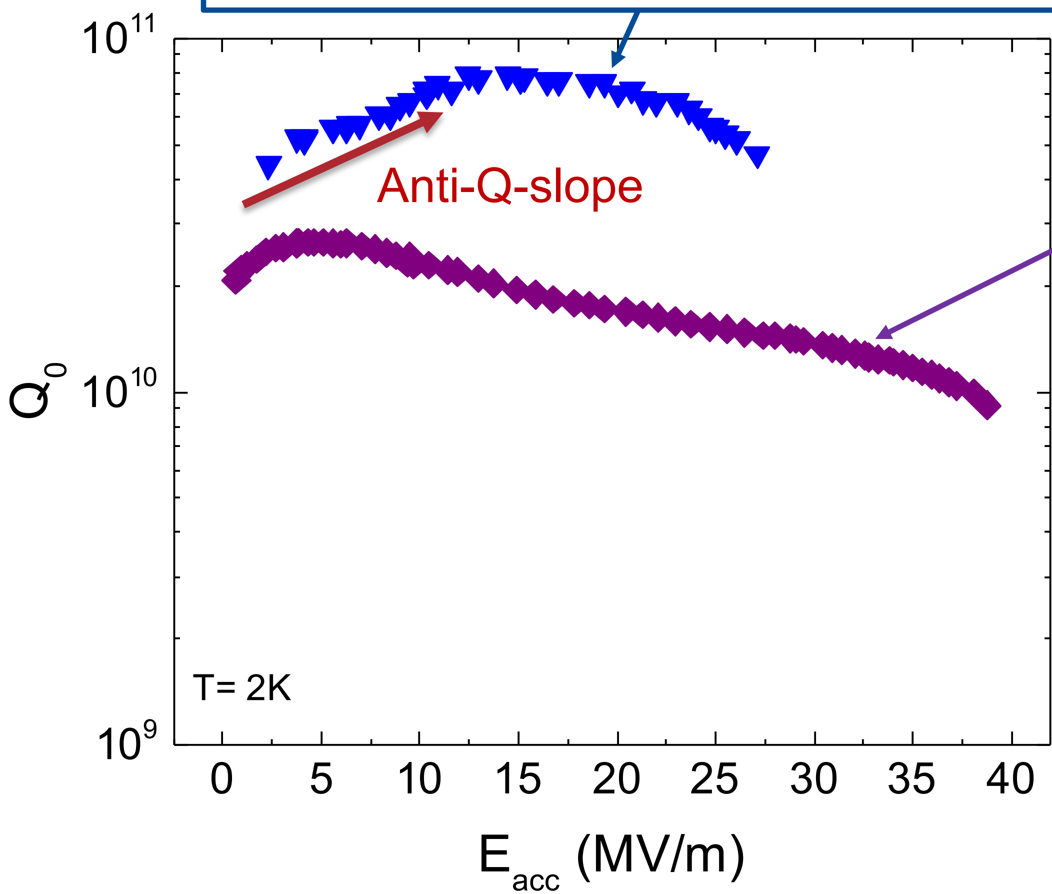
Established technology for high-Q and high gradient

N-doping: very high Q-factors at 15-20 MV/m, quench field usually < 30 MV/m

120C baking: capability to reach high gradients 35-45 MV/m with Q < 10^{10}



A. Grassellino et al., Supercond. Sci. Technol. **26**, 102001 (2013) – Rapid Communications

High-Q and high-gradient treatments for SRF cavities

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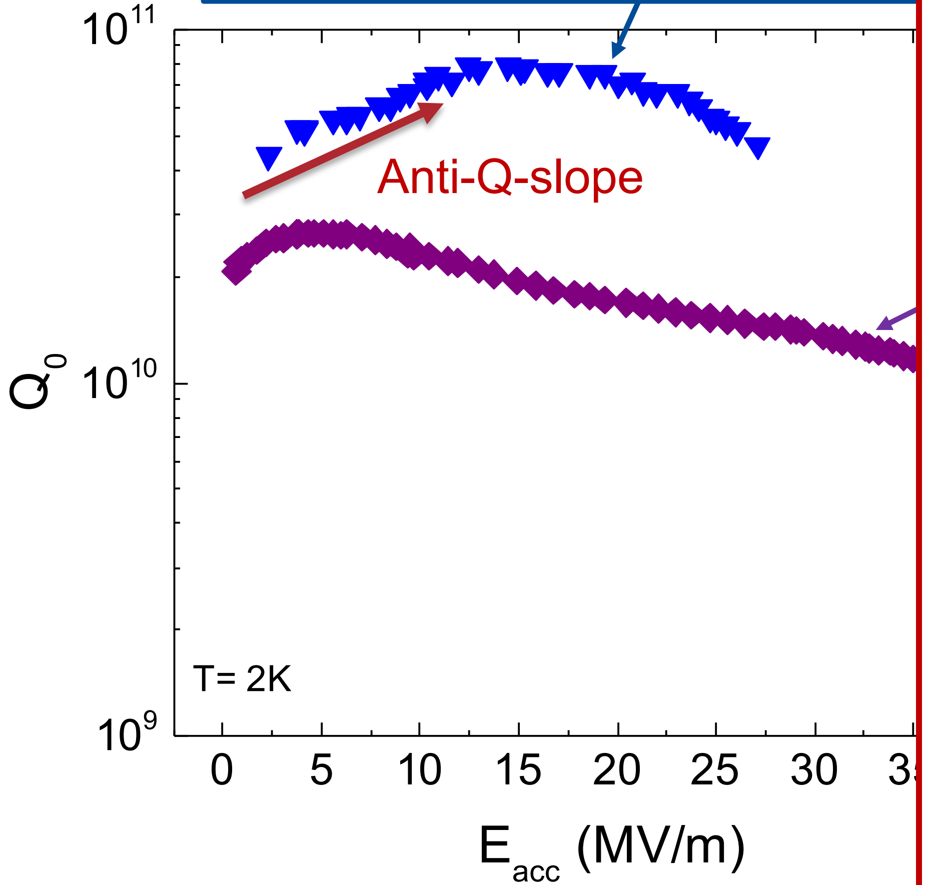
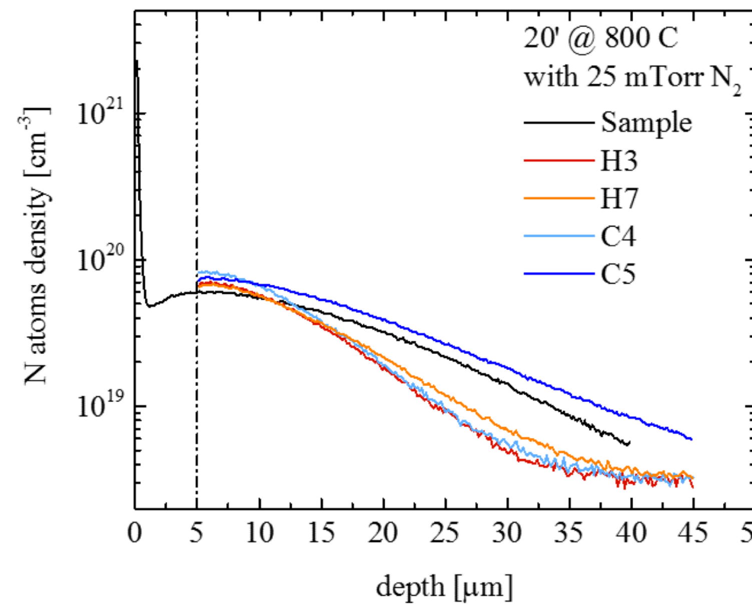


N Doping at T> 800C manipulate mean free path constantly throughout several microns, **giving the highest Q**

N doping: nitrogen throughout several microns



A. Grassellino et al, Proceedings of SRF 2015

A. Grassellino et al., Supercond. Sci. Technol. **26**, 10200 … Rapid Communications

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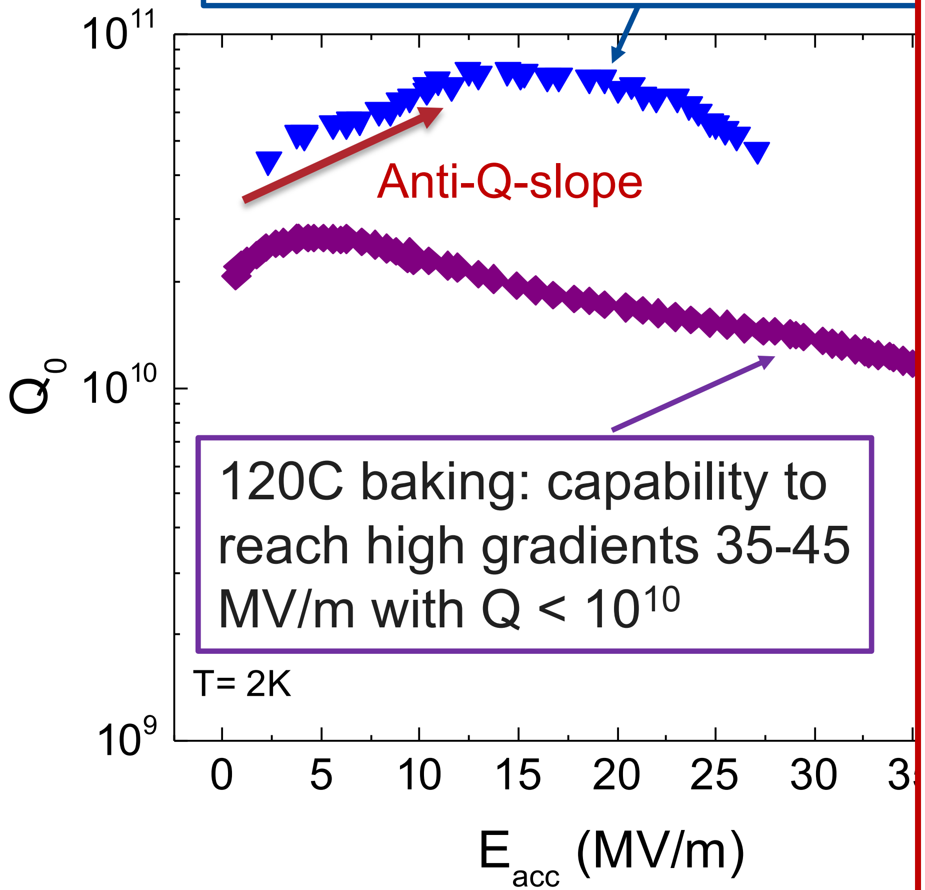
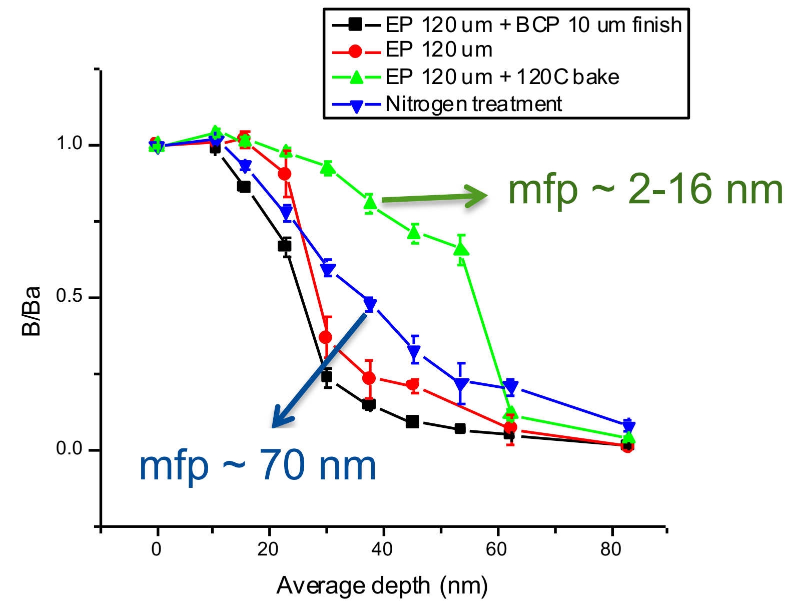


120C bake known to manipulate mean free path at very near surface on clean bulk, **giving the highest gradients**

120C bake, vacancies in first ~ 60 nanometers



A. Romanenko et al, Appl. Phys. Lett. 102, 232601 (2013)

A. Grassellino et al., Supercond. Sci. Technol. **26**, 102001 (2013) – Rapid Communications

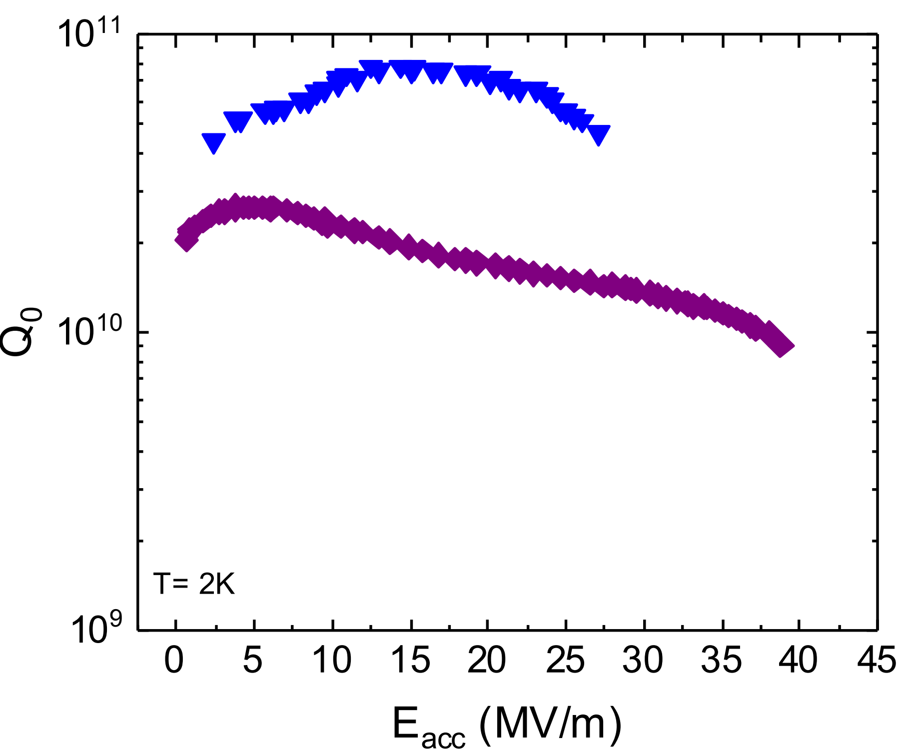
N-infusion: high-Q at high-gradients

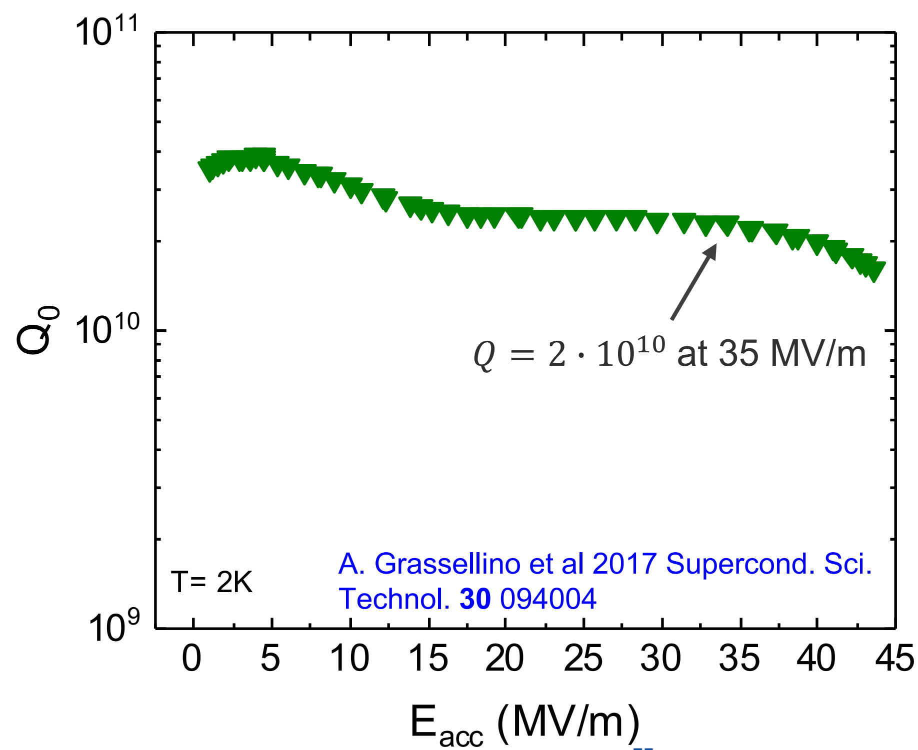
Composition and mean free path in first nanometers of cavity surface have been shown to be crucial for both Q and gradient performance

N Doping (high-Q)
+
120C baking (high gradients)

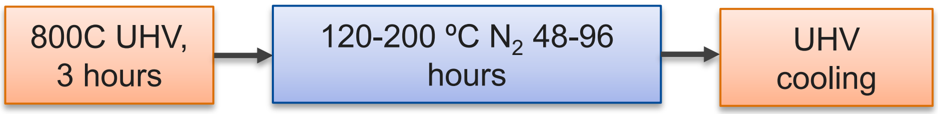
→

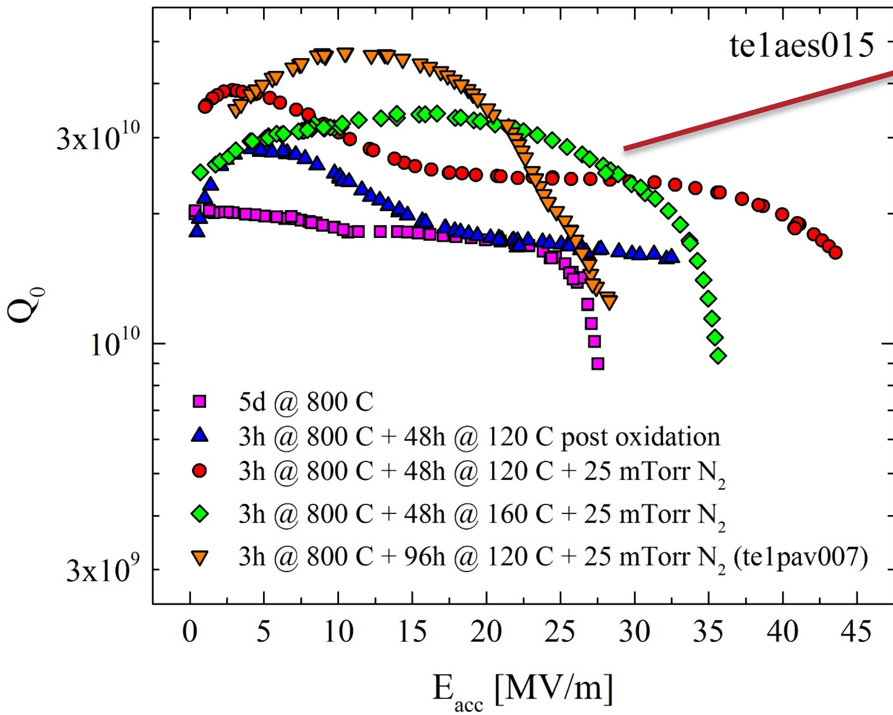
N-infusion: high-Q at high gradients





N-infusion processing sequence





Performances can be optimized to reach high-Q at different gradients by varying the main parameters (T, time)

- Different nitrogen depth profiles within λ change performance dramatically

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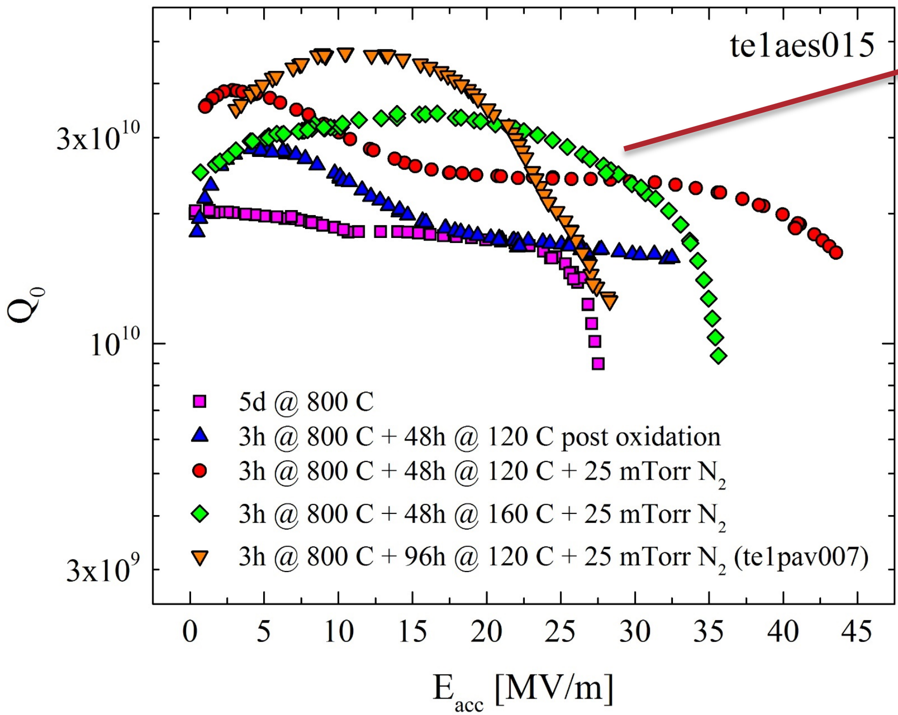
N-infusion processing sequence

800C UHV, 3 hours → 120-200 ºC N_2 48-96 hours → UHV cooling



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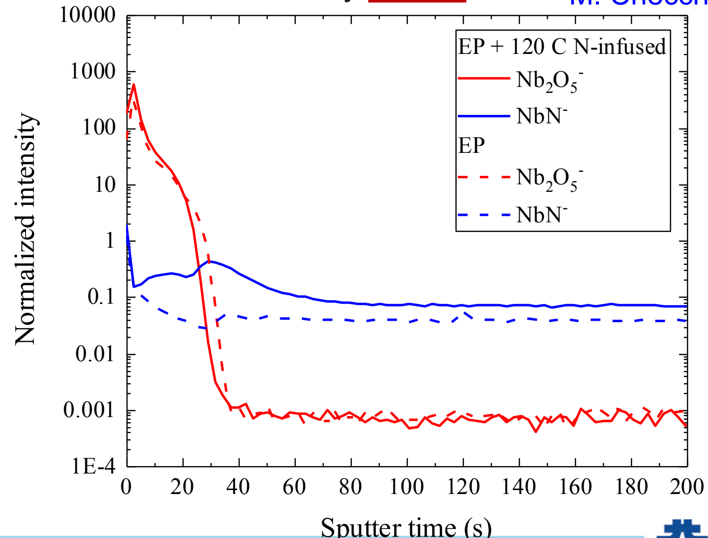
- Different nitrogen depth profiles within λ change performance dramatically

Comparison EP and 120 C 48h N-infused cavity **cutout**

M. Checchin, TTC Milan 2018



Nitrogen penetrates for ~20 nm with N-infusion at 120C for 48 hours

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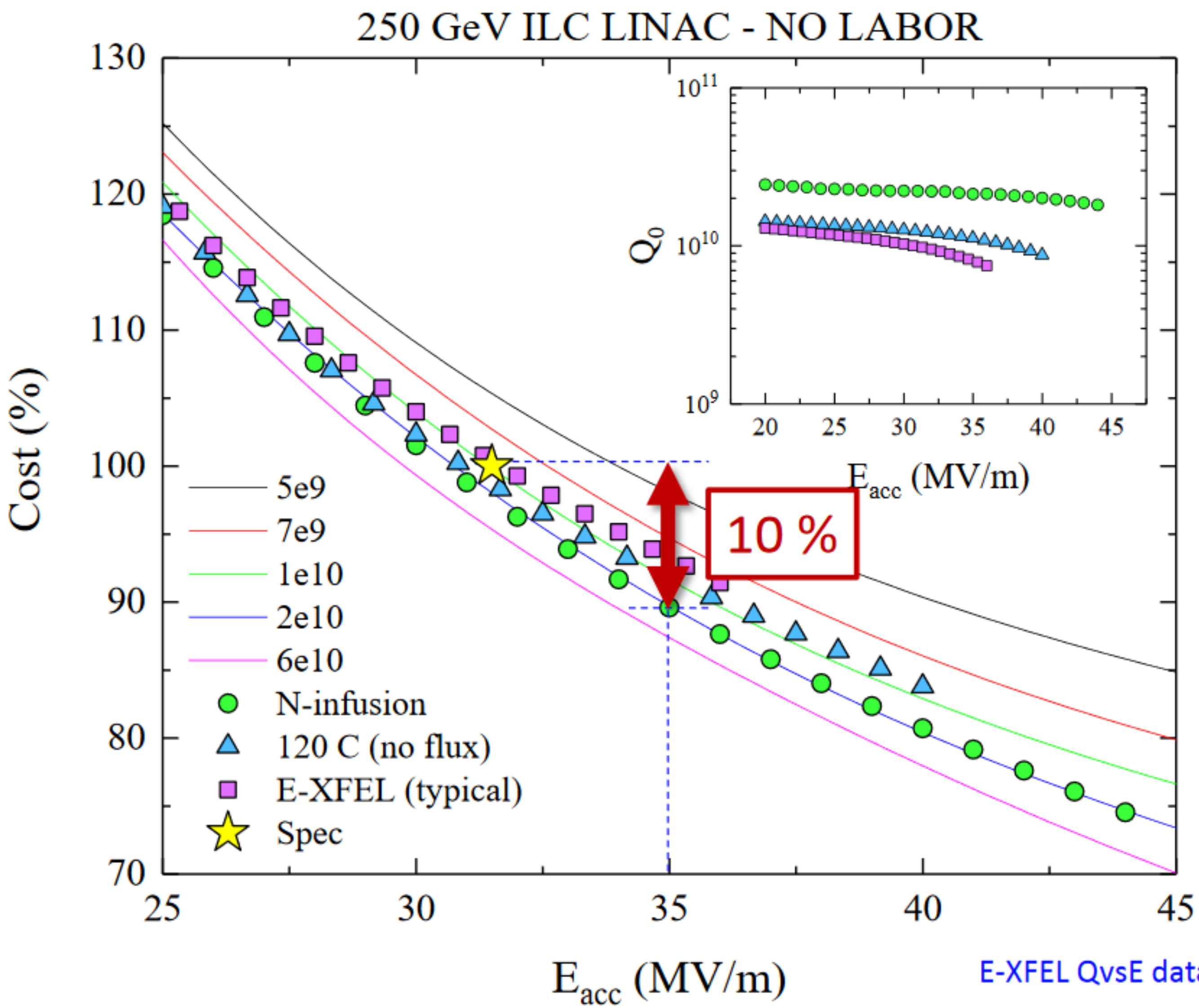
ILC LINAC cost reduction with N-infusion



E-XFEL QvsE data courtesy of N. Walker

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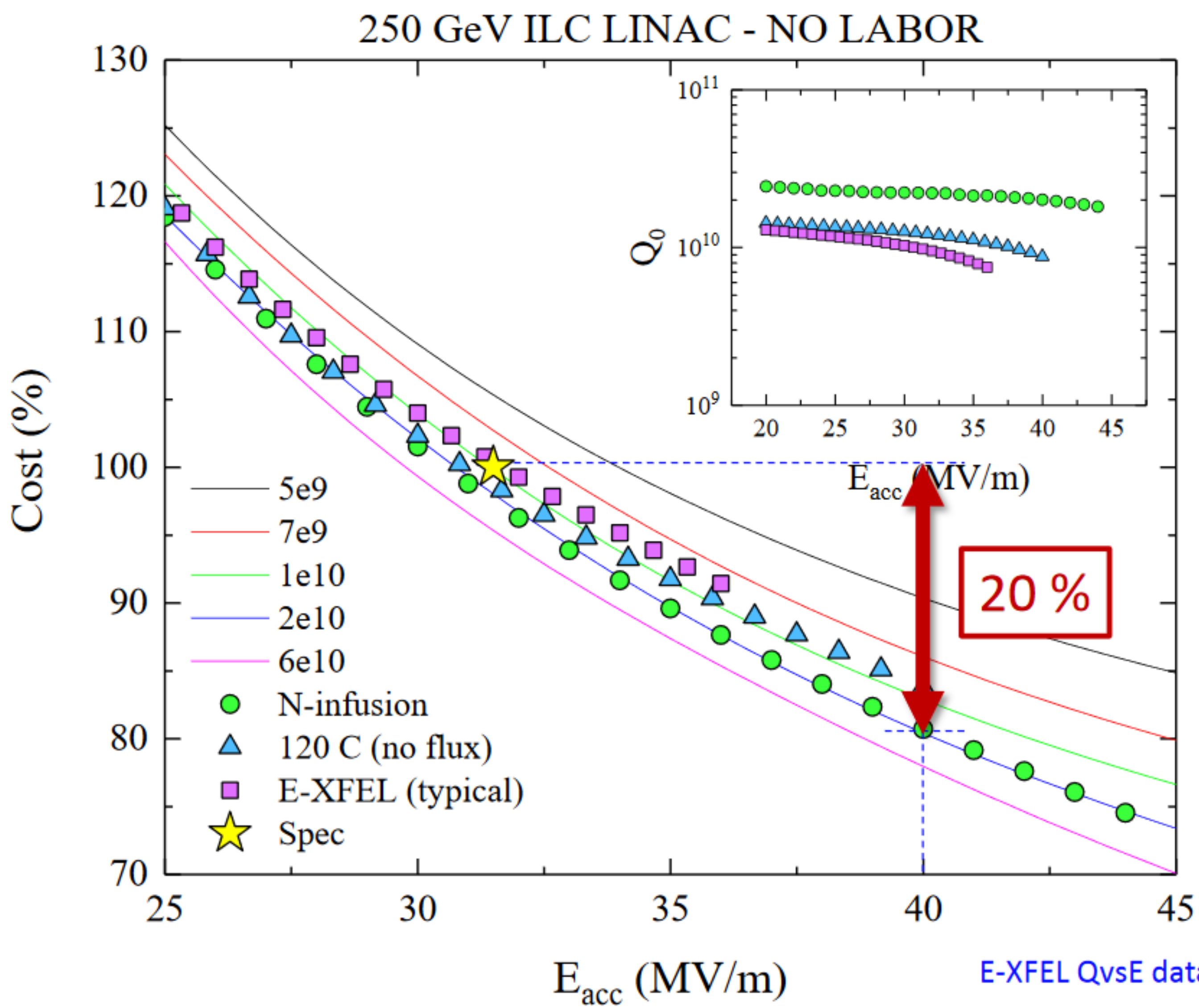

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- Recent SRF R&D results at Fermilab:
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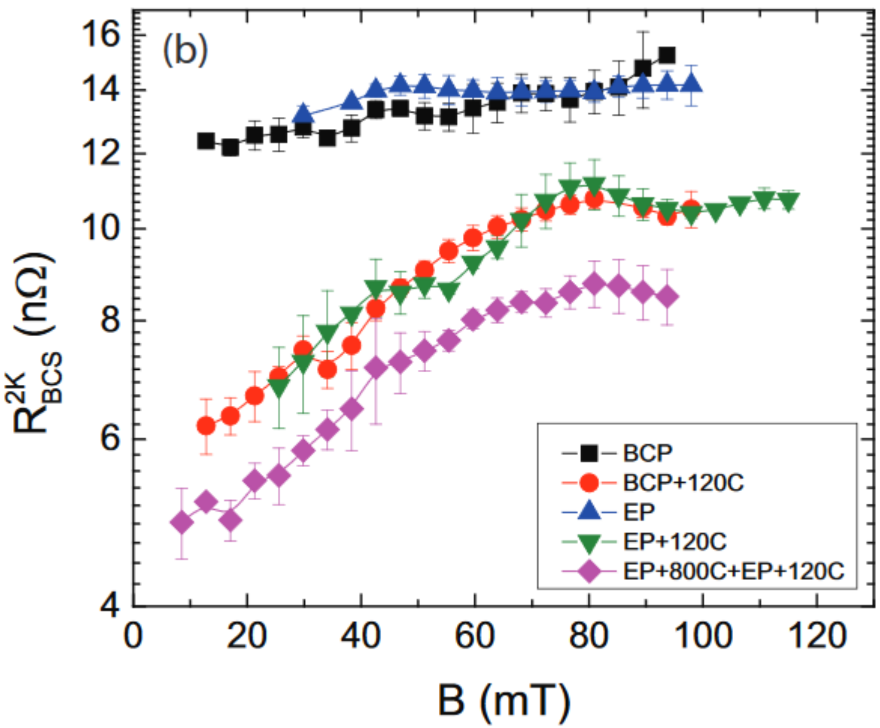
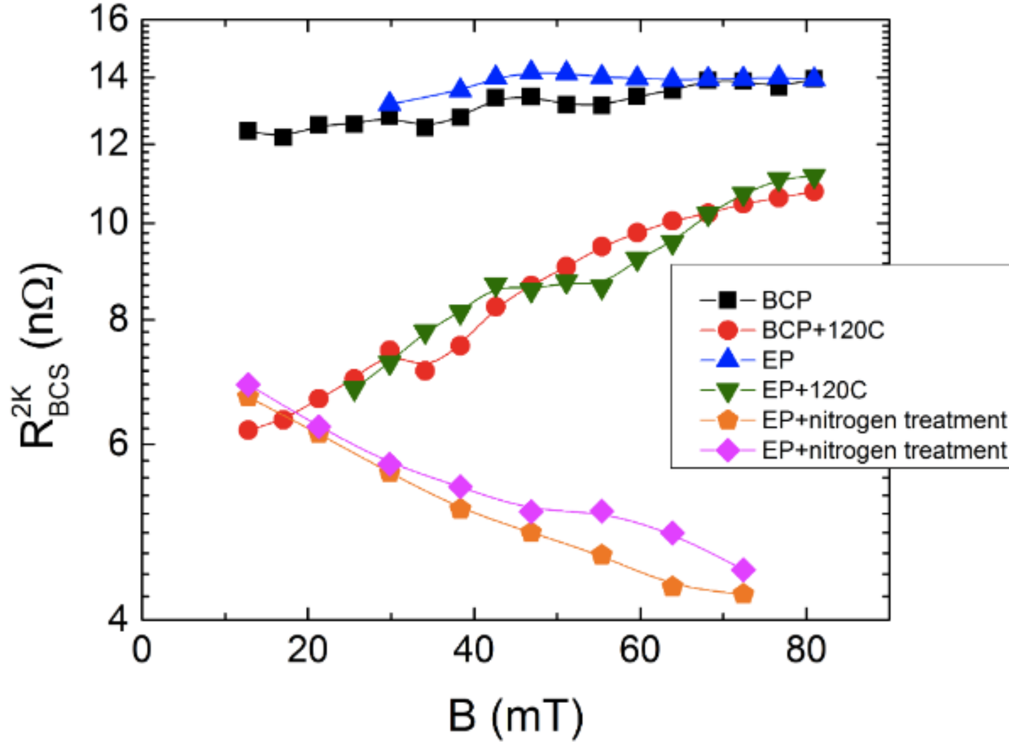
R_{BCS}(Eacc) at 1.3 GHz





A. Romanenko and A. Grassellino, *Appl. Phys. Lett*. **102**, (2013)
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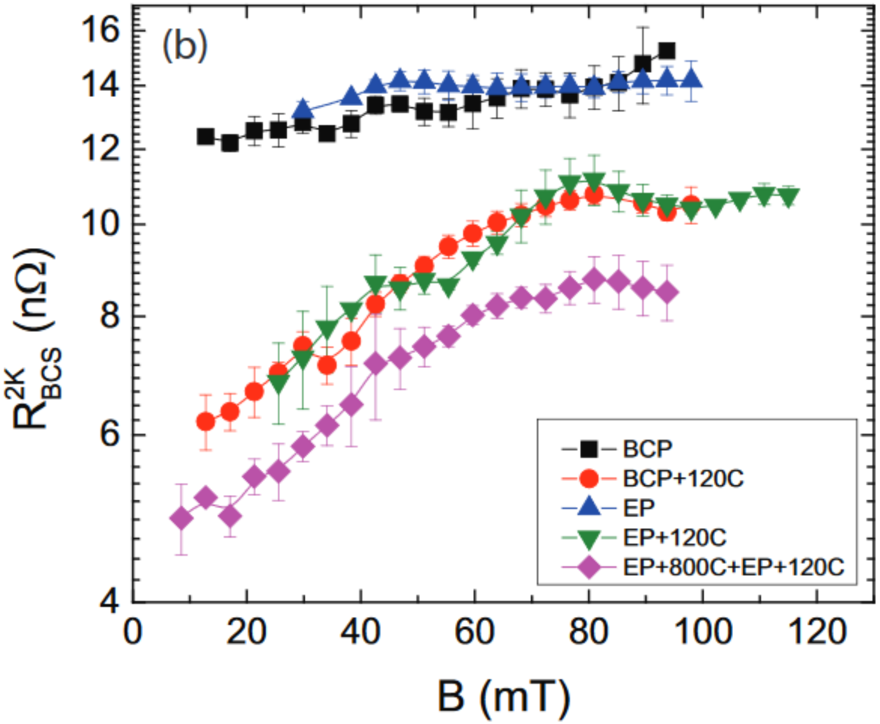
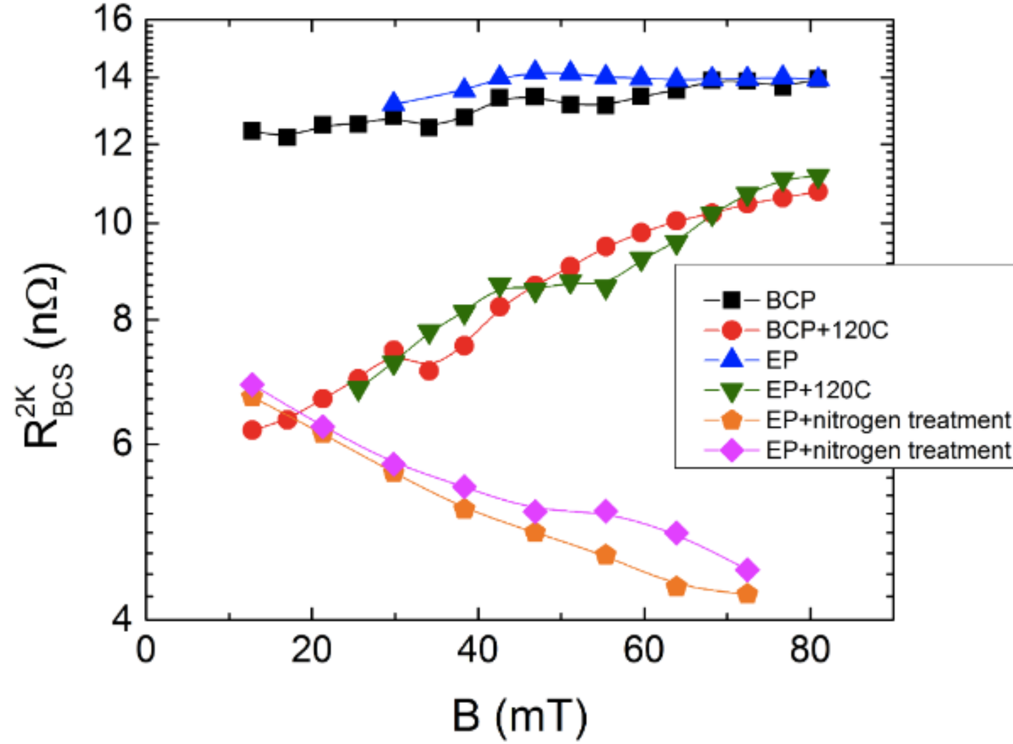
From 1.3 GHz data we know that:

- $R_{BCS}(E_{acc})$ increases in regular niobium cavities (EP, BCP, 120C baking)
- $R_{BCS}(E_{acc})$ decreases in N-doped niobium cavities

R_{BCS}(Eacc) at 1.3 GHz





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- $R_{BCS}(E_{acc})$ increases in regular niobium cavities (EP, BCP, 120C baking)
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How do these field dependences change with the frequency?

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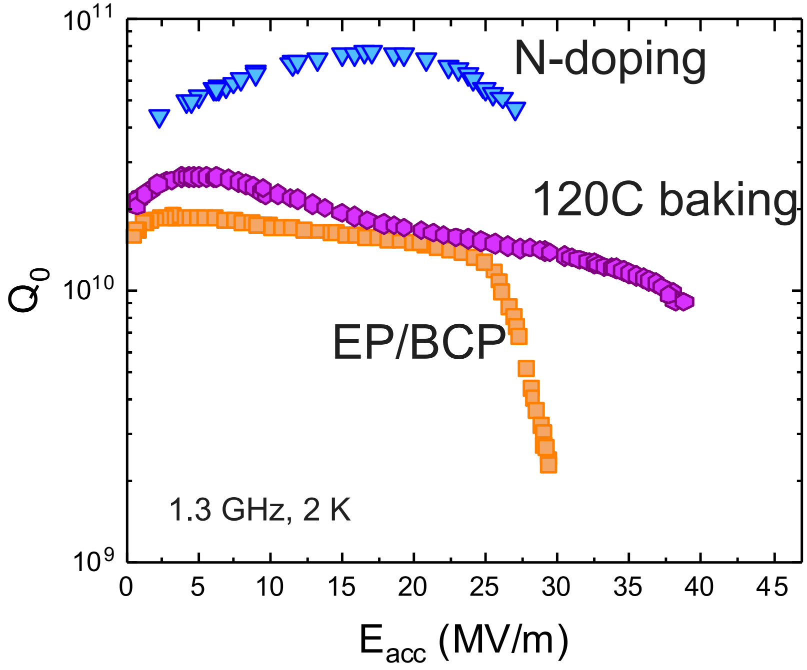
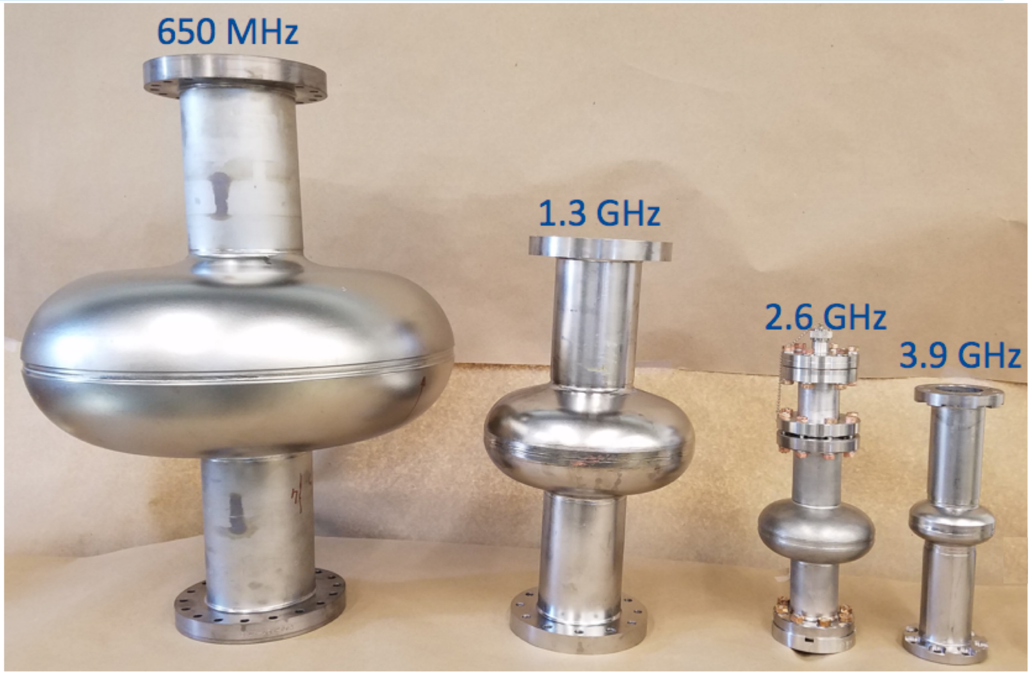
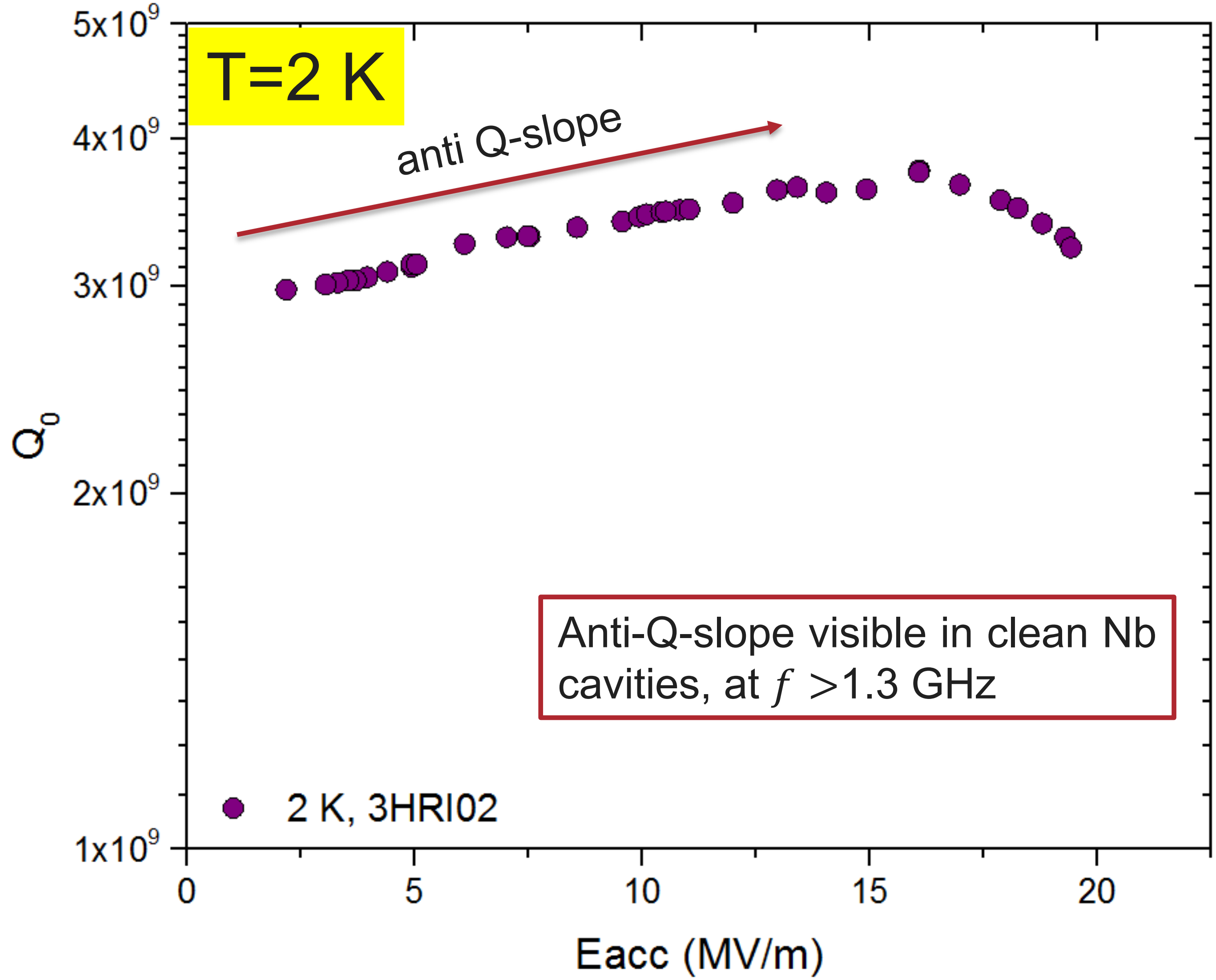
Analyzed Cavities





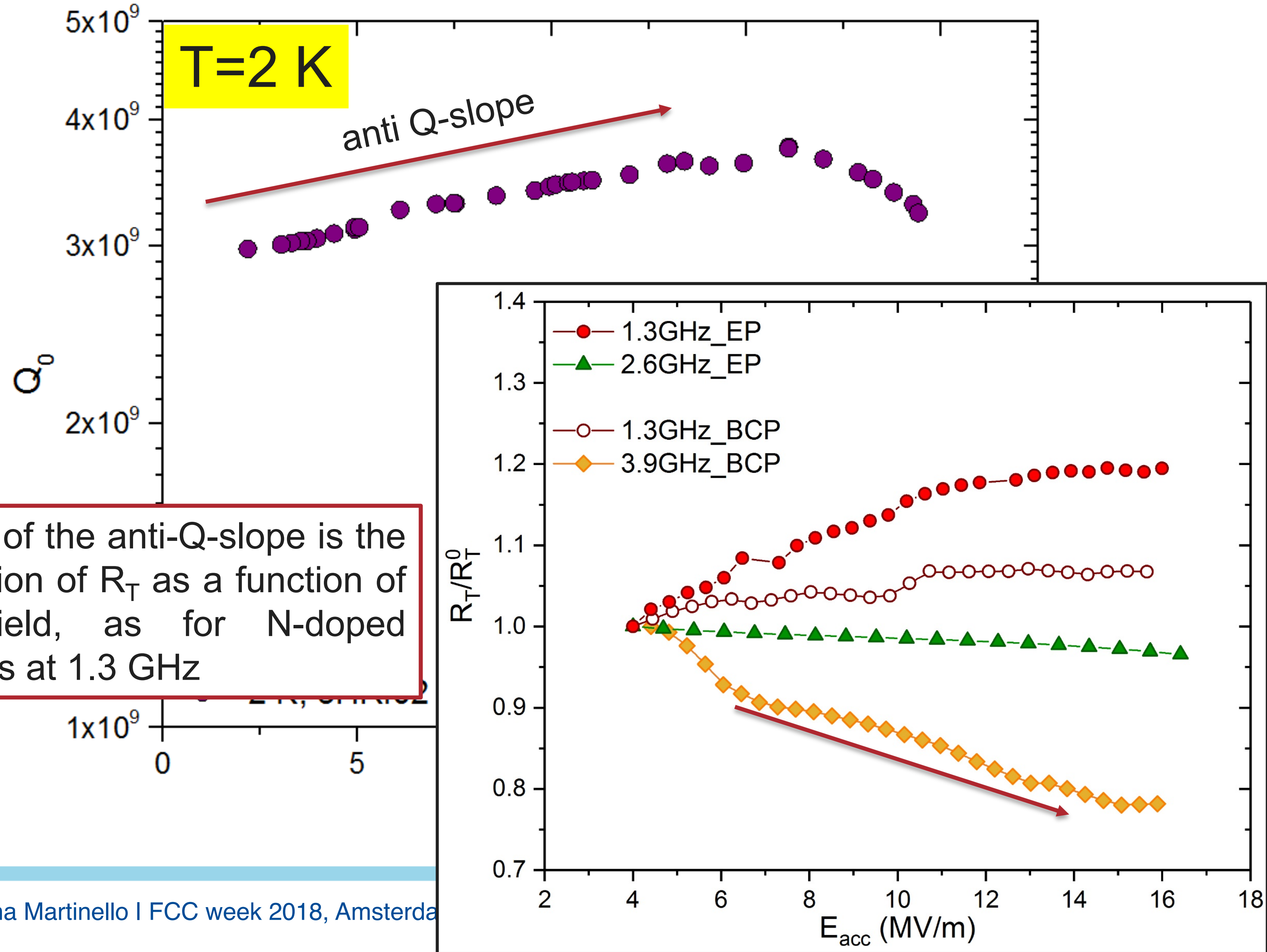
	650 MHz	1.3 GHz	2.6 GHz	3.9 GHz
EP		✓	✓	
BCP		✓		✓
120 C baking	✓	✓	✓	✓
2/6 N-doping	✓	✓	✓	✓

Anti Q-slope in BCP'd 3.9 GHz Cavities



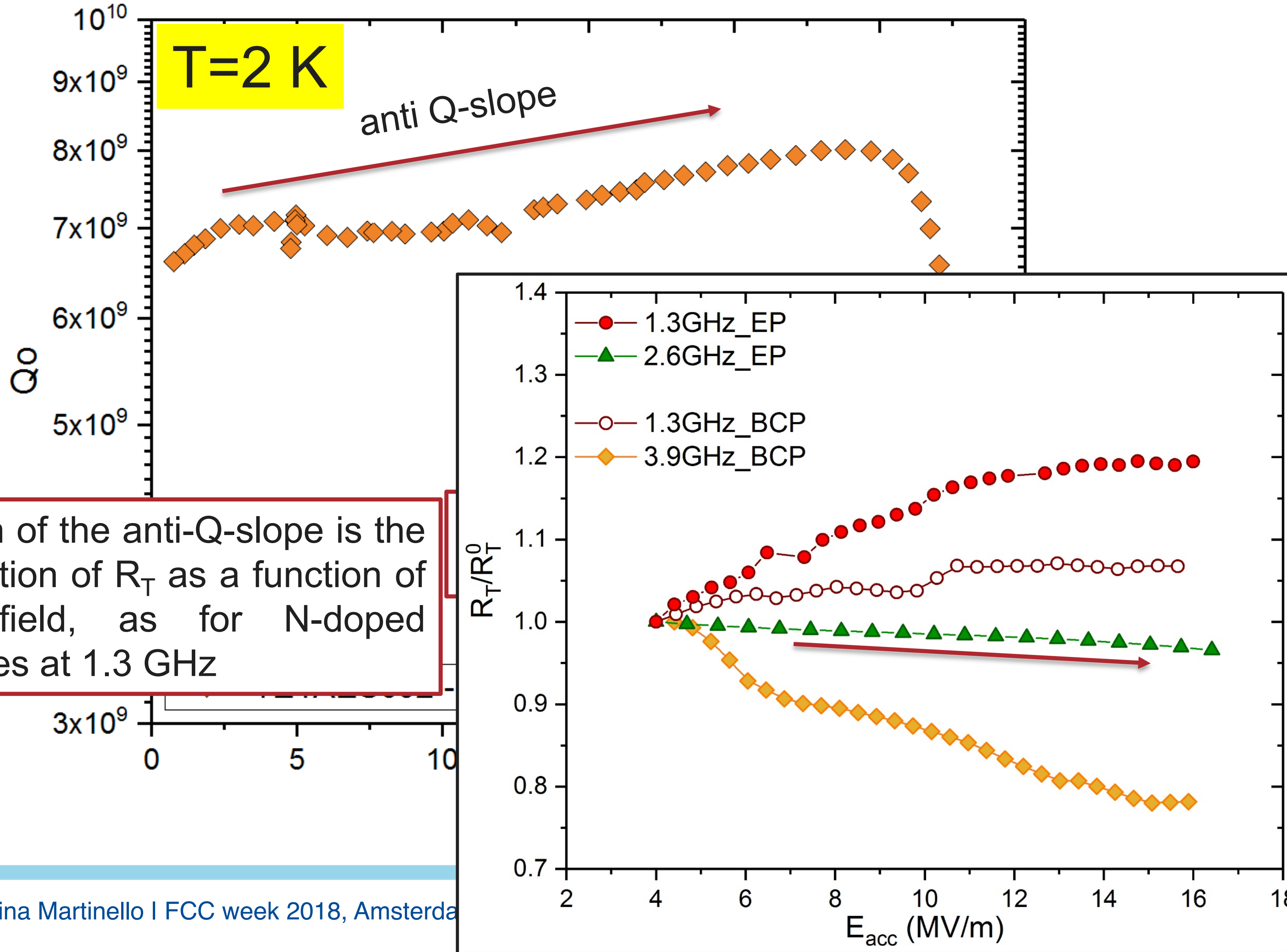
Anti-Q-slope visible in clean Nb cavities, at f >1.3 GHz

Anti Q-slope in BCP'd 3.9 GHz Cavities



Origin of the anti-Q-slope is the reduction of R_T as a function of the field, as for N-doped cavities at 1.3 GHz

Anti Q-slope in EP'ed 2.6 GHz Cavities



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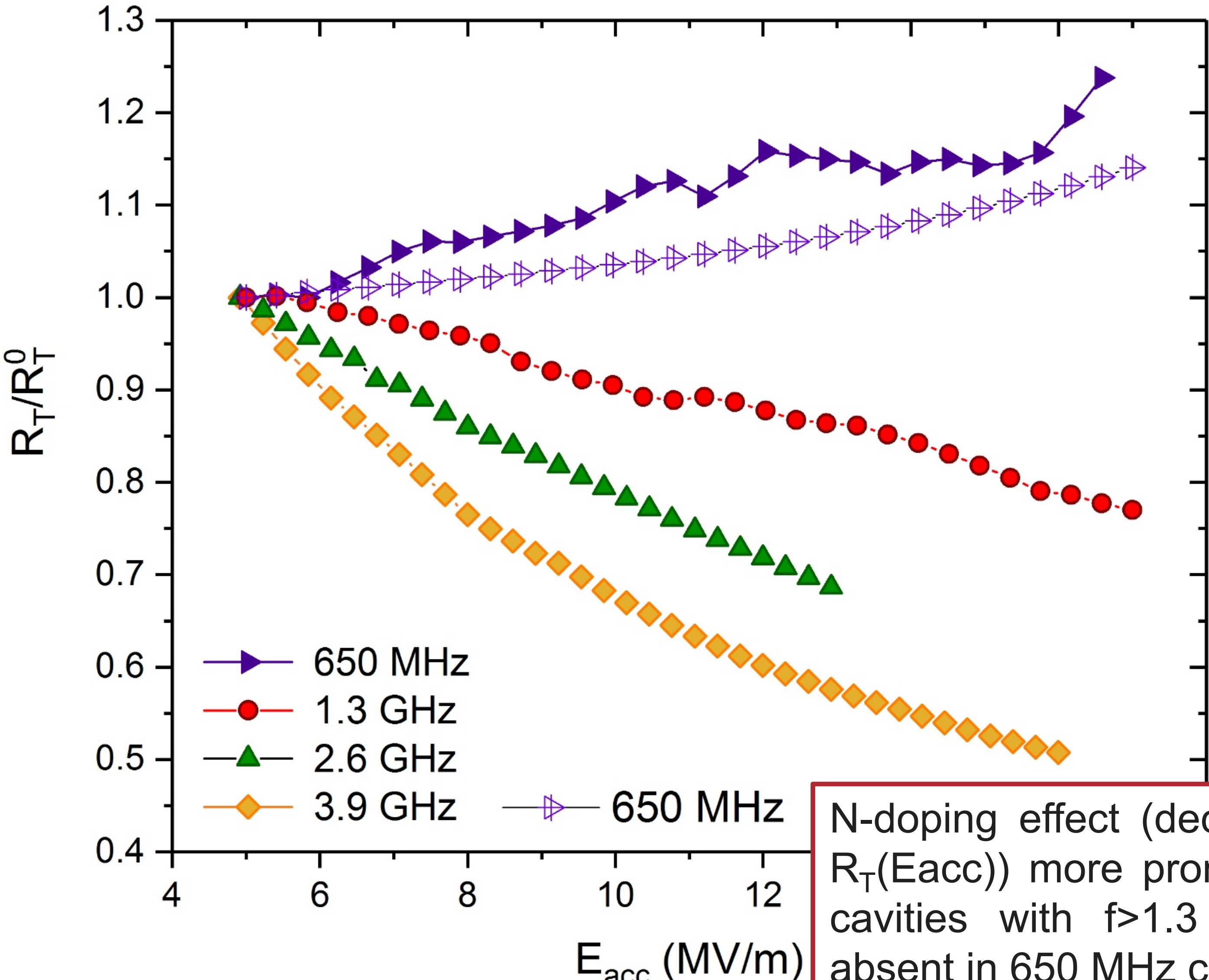
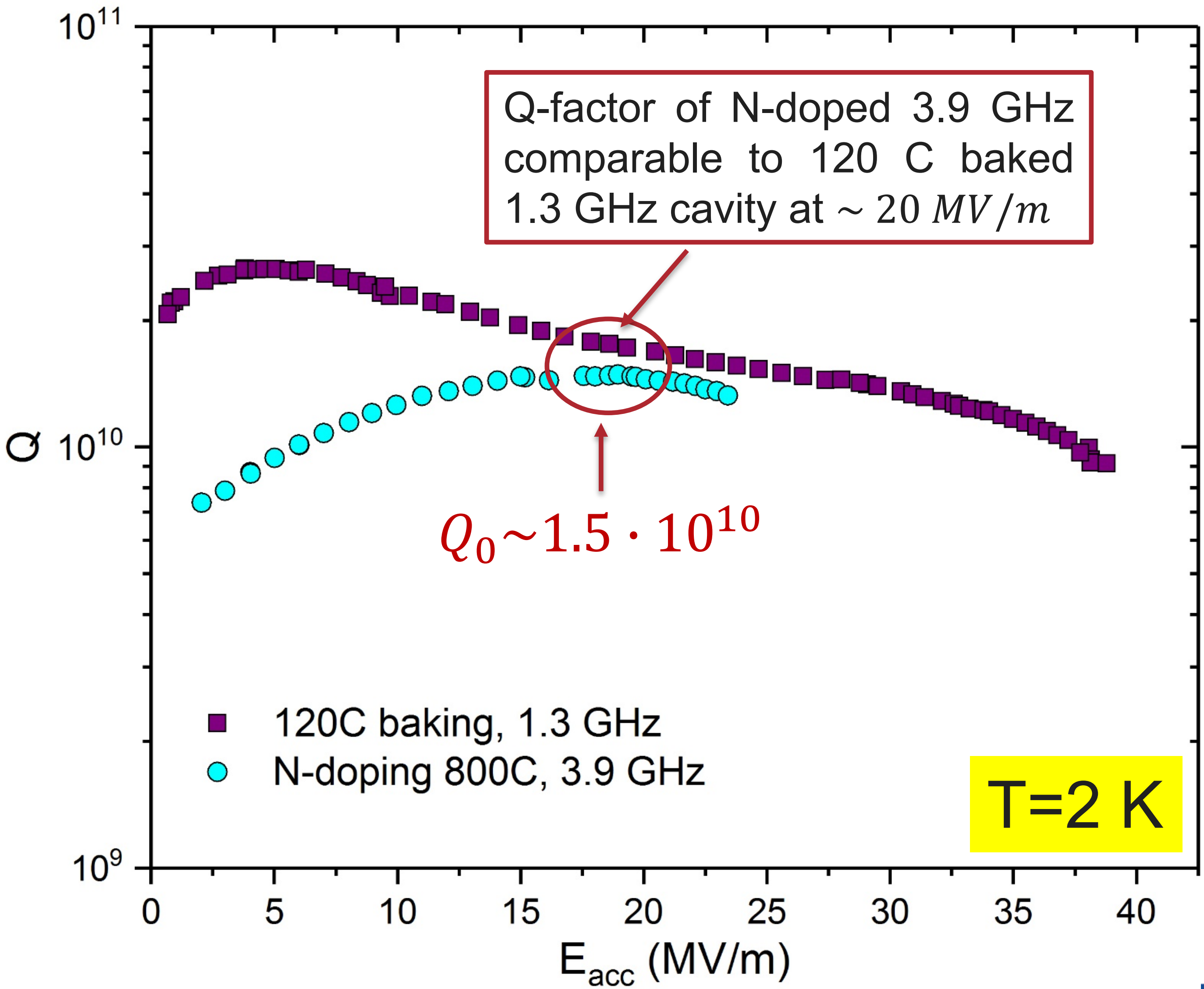
3. Normalized $R_T(2\ K)$ for N-doping



N-doping effect (decreasing of R_T(Eacc)) more pronounced in cavities with f>1.3 GHz and absent in 650 MHz cavities

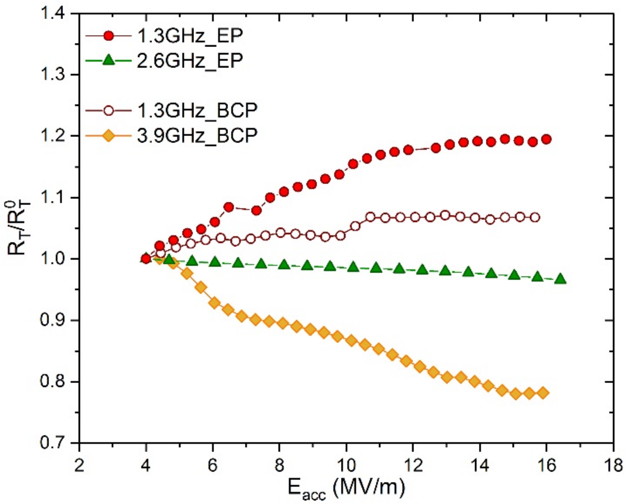
*Some measurements were admin limited between 15-20 MV/m to avoid quench so, in order to compare the different curves, only data till ~17 MV/m are shown

Unprecedented Medium Field Q_0 at 3.9 GHz

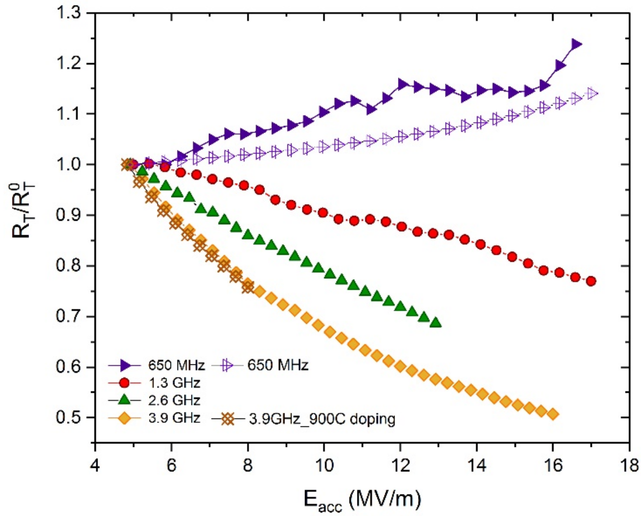


Summary on the frequency dependence of R_{BCS}(Eacc)

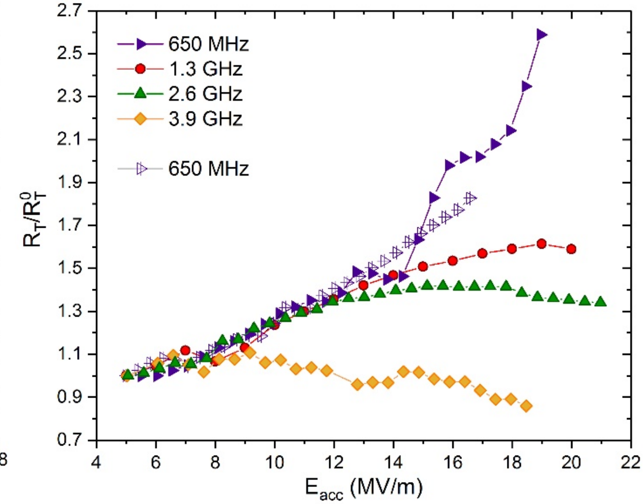
EP/BCP



N-doping



120C baking



- The physical mechanism underneath the R_T reversal has a stronger effect at high frequencies
- The R_T reversal, that has been considered the signature of the N-doped treatment, is actually visible also in clean Nb but at high frequency
- On the other hand, N-doped cavities at low frequencies do not show the R_T reversal observed at 1.3 GHz

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Summary on the frequency dependence of R_{BCS}(Eacc)

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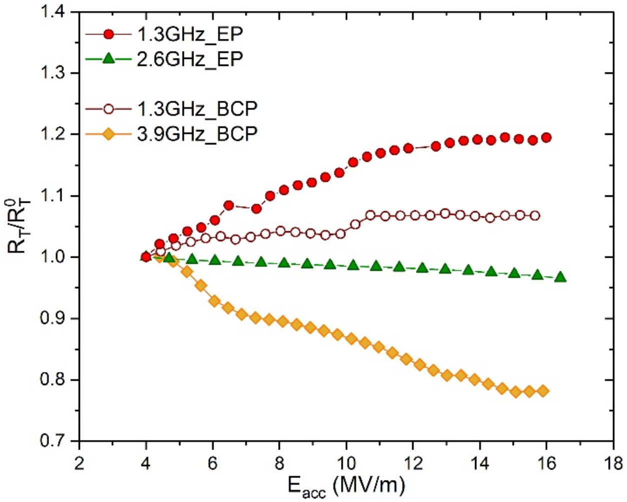

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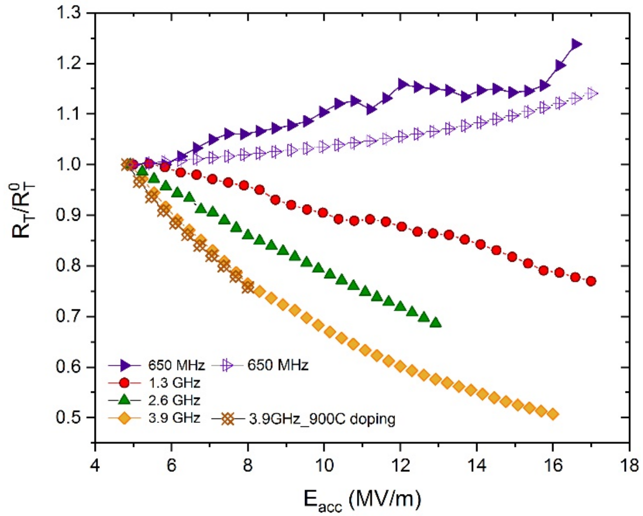

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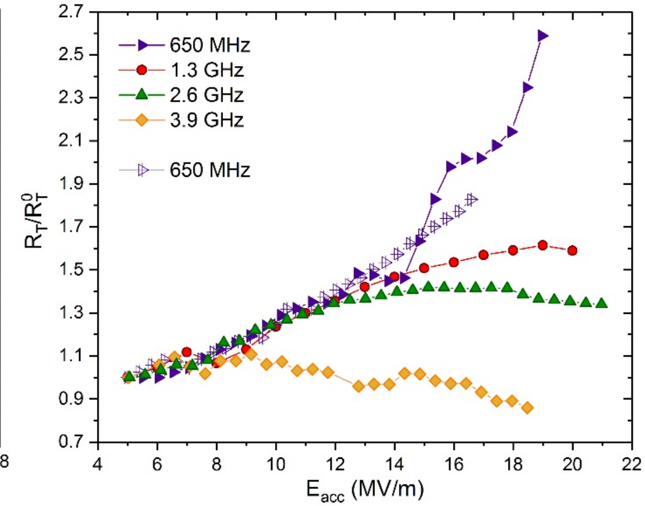

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- Th e N- d high fre

Non-equilibrium distribution of quasi-particles may qualitatively explain this behavior.

If interested in more details, see: M. Martinello, TTC Milan 2018

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- Recent SRF R&D results at Fermilab:
  - High-Q at high gradients
  - Frequency dependence of the surface resistance
  - Nb_3Sn
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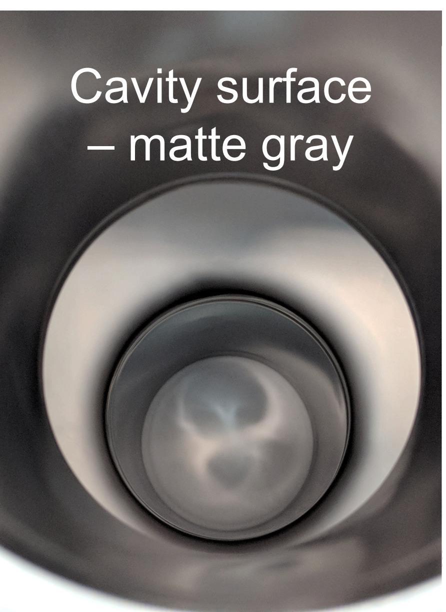
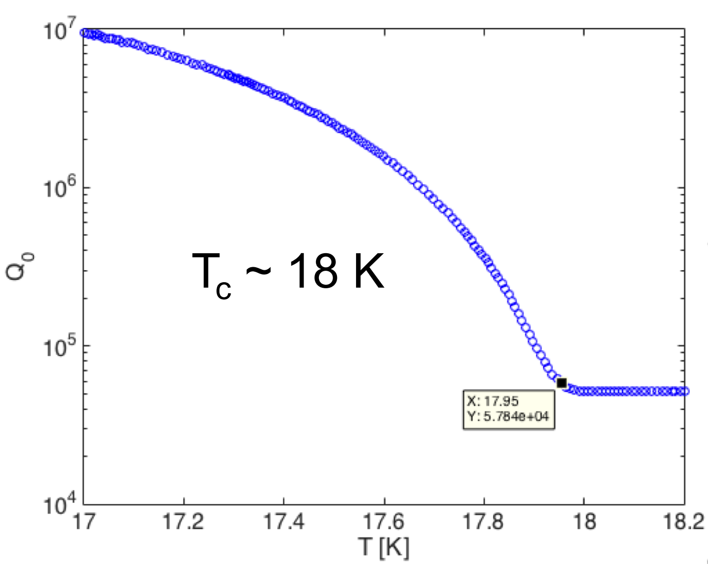
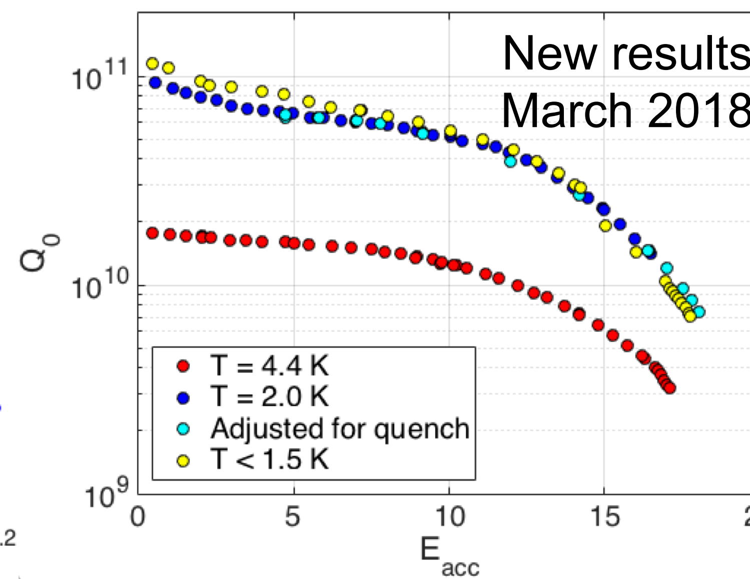
Nb_3Sn Coatings for High Q_0

Courtesy of S. Posen

- With a critical temperature of 18 K, Nb_3Sn at 4.4 K can have similar Q_0 to Nb at 2.0 K
- Cryogenic plant at 4.4 K vs 2.0 K: efficiency is 3-4 times better, capital costs are smaller, higher reliability…
- In last ~5 years, substantial improvements to Nb_3Sn cavity performance under Cornell program
- New Fermilab program now achieving good performance on 1-cell 1.3 GHz cavities—larger cavities to be coated soon



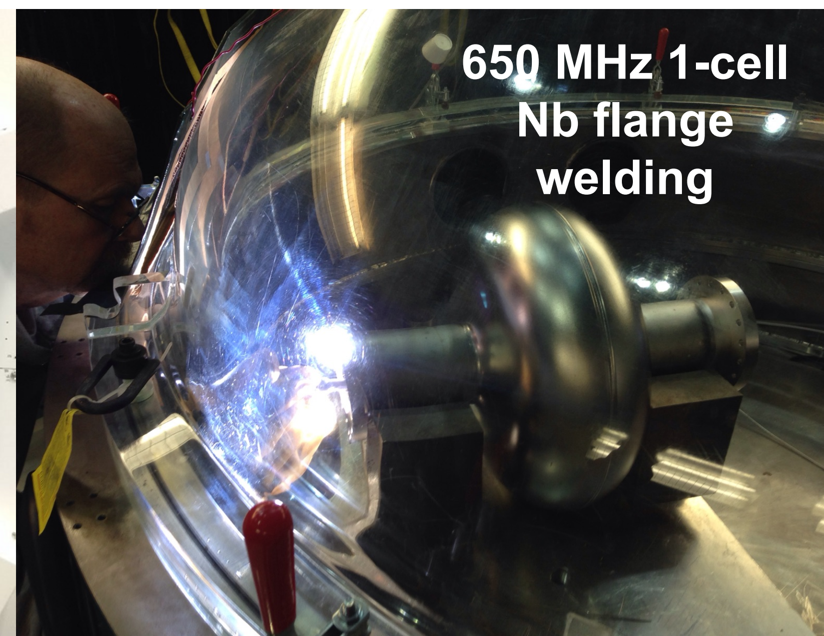




Nb_3Sn Coatings for High Q_0

Courtesy of S. Posen

- Very soon pushing into lower frequency regime relevant for FCC – 650 MHz cavity recently welded
- Coating chamber was designed to hold 650 MHz 5-cell cavities – multicells also in development
- R&D program continued development to push E_{acc} and Q_0
- Collaboration underway with CERN to coat 800 MHz 1-cell



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4.4 K Comparison: N-doping vs Nb_3Sn @ 1.3 GHz

SRF cavities for FCC-ee:

FCC-ee W

	OPTION 1	OPTION 2
Frequency in MHz	400	400
Technology	Nb/Cu	Bulk Nb
E_{acc} in MV/m	10	
Temperature in K	4.5	2.0
# of cells/cavity	1 – 4	
# of cavities FCC W	428 – 108	
# of CM for FCC W	108 – 28	

FCC-ee Higgs & top

	OPTION 1	OPTION 2
Frequency in MHz	400	800
Technology	Nb/Cu	Bulk Nb
E_{acc} in MV/m	10	20
Temperature in K	4.5	2.0
# of cells/cavity	3 – 5	
# of cavities FCC H	534 – 322	
# of cavities FCC t	846 – 508	
# of CM for FCC H	134 – 82	
# of CM for FCC t	212 – 127	

S. Aull, FCC 2017

Technology comparison for FCC-ee:

- N-doping: high-Q at medium field
- Nb_3Sn: higher Tc

Potential of these technologies to frequencies useful for FCC

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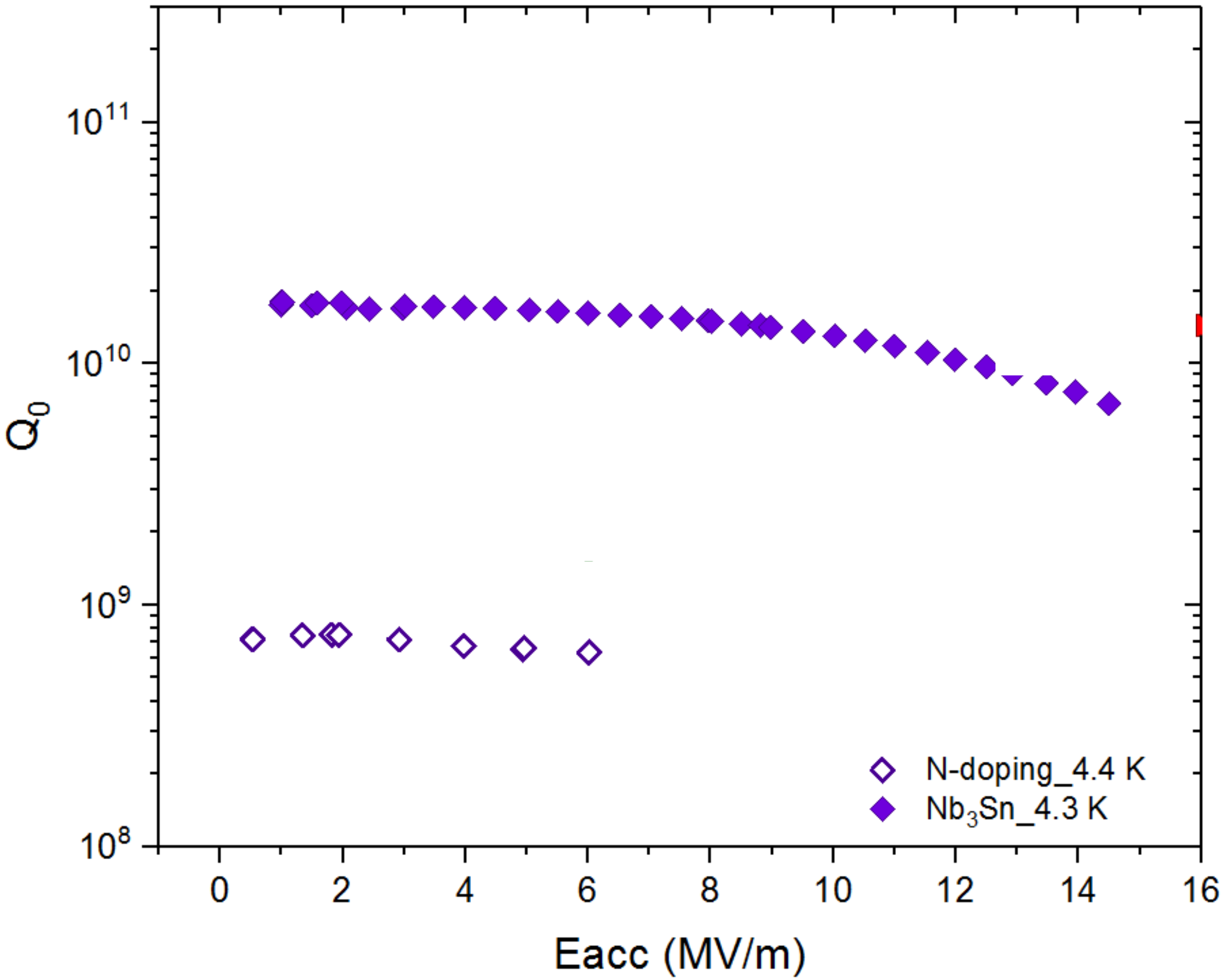
4.5 K Comparison: N-doping vs Nb_3Sn @ 1.3 GHz



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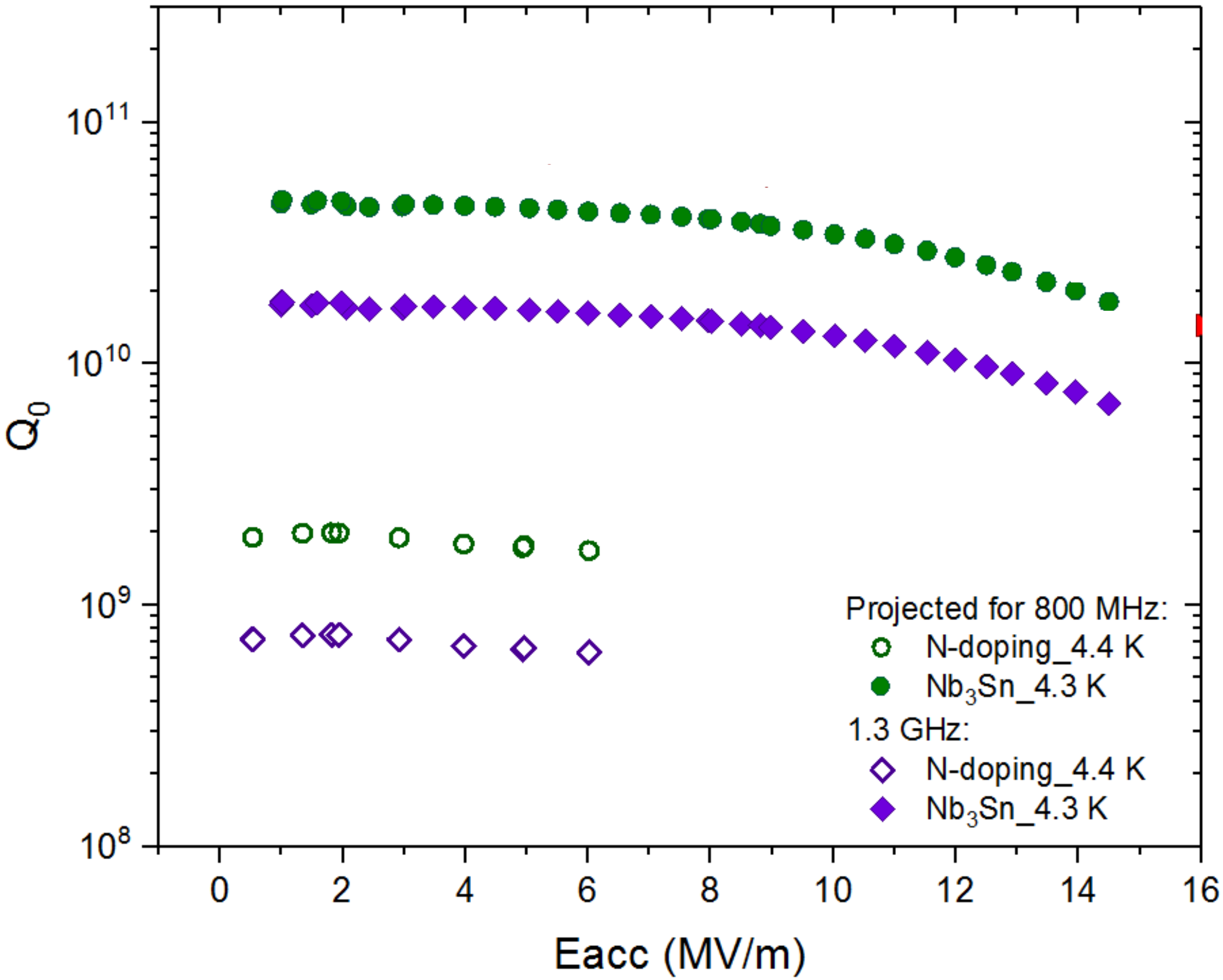

WARNING:
Projected values calculated with very crude f^2 scaling law

- Field dependence variation with frequencies is not taken into account
- In both cases (N-doping and Nb3Sn values at high fields are overestimated)

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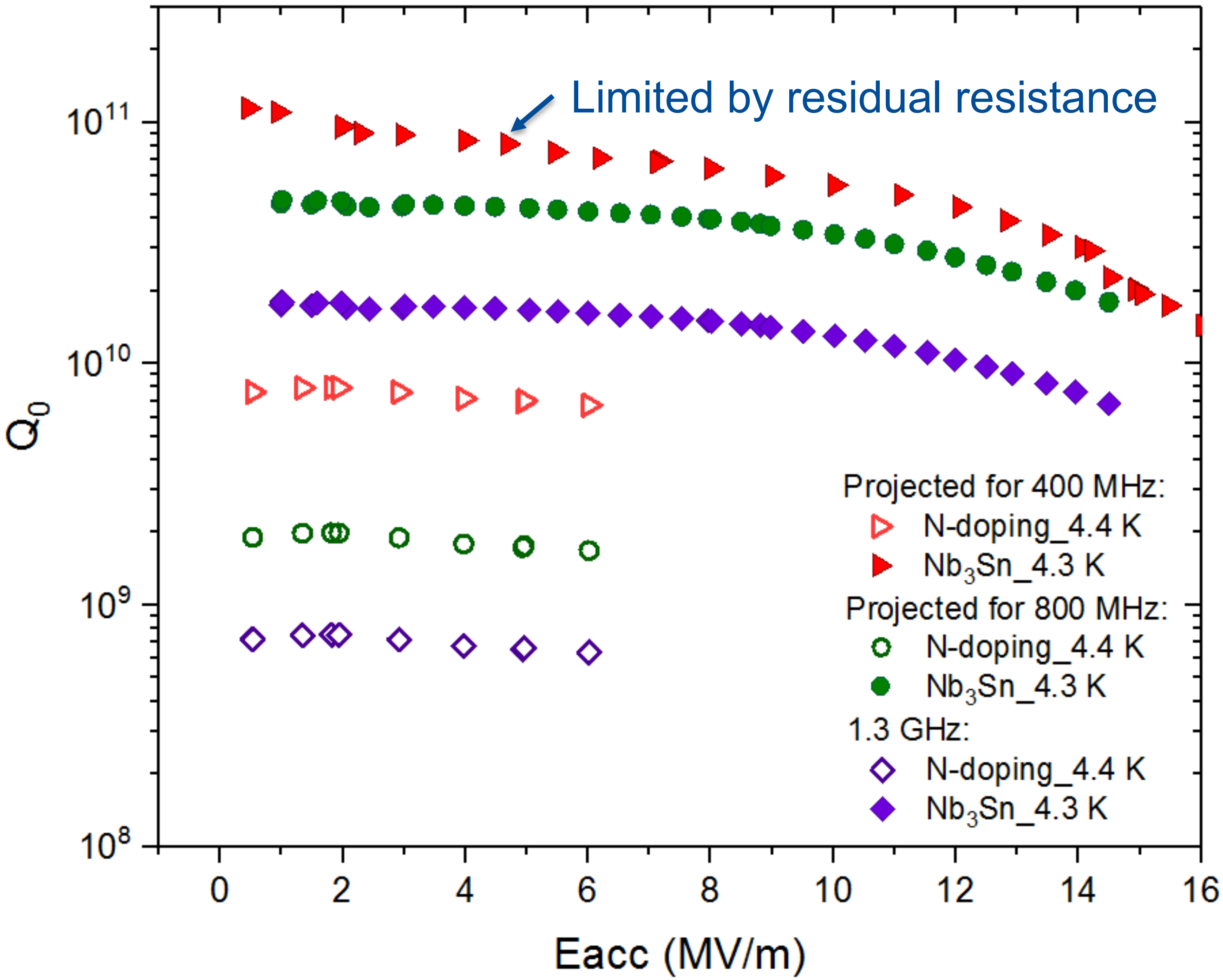

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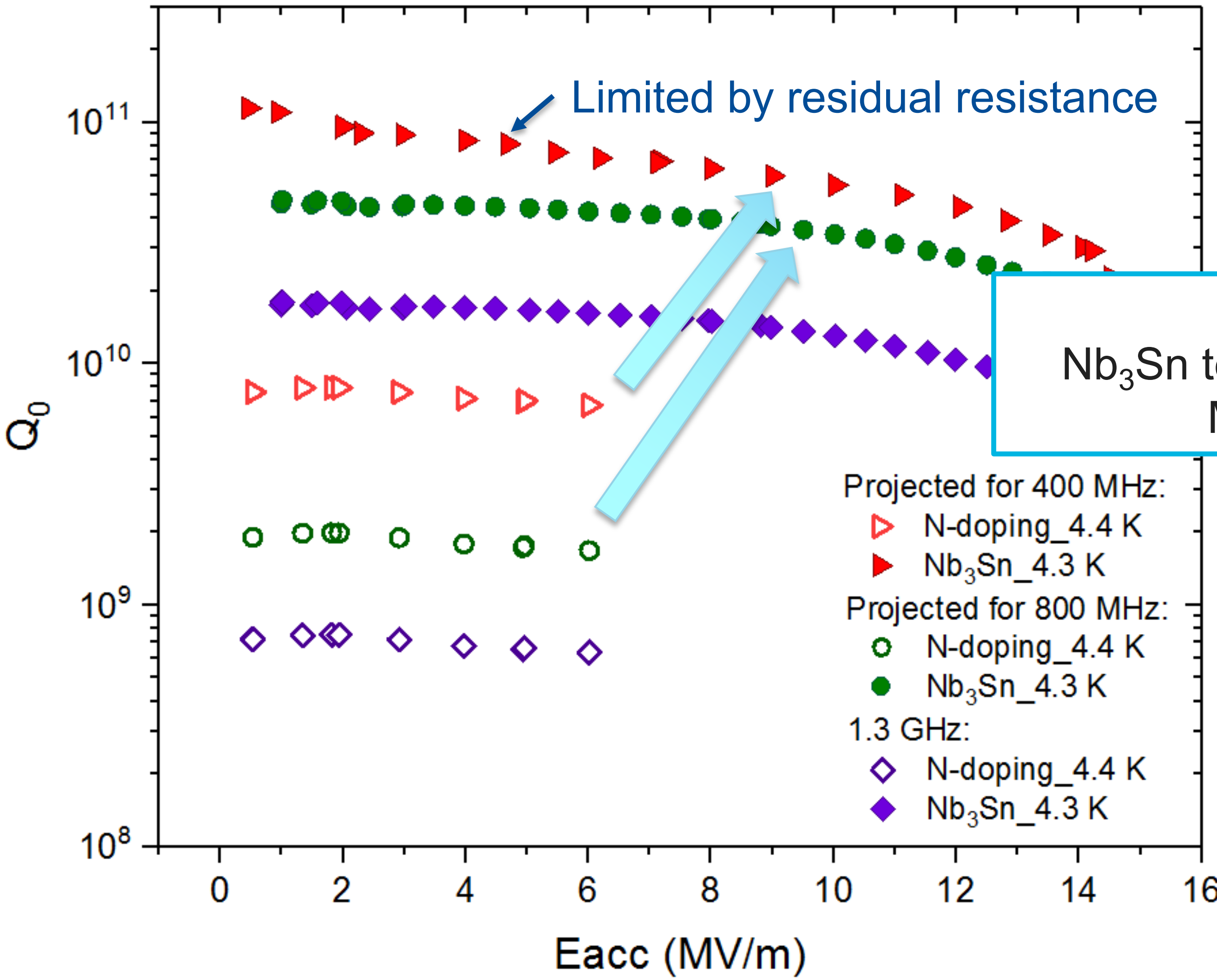

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Gain given by Nb_3Sn technology @ 400/800 MHz, 10 MV/m

taken into account

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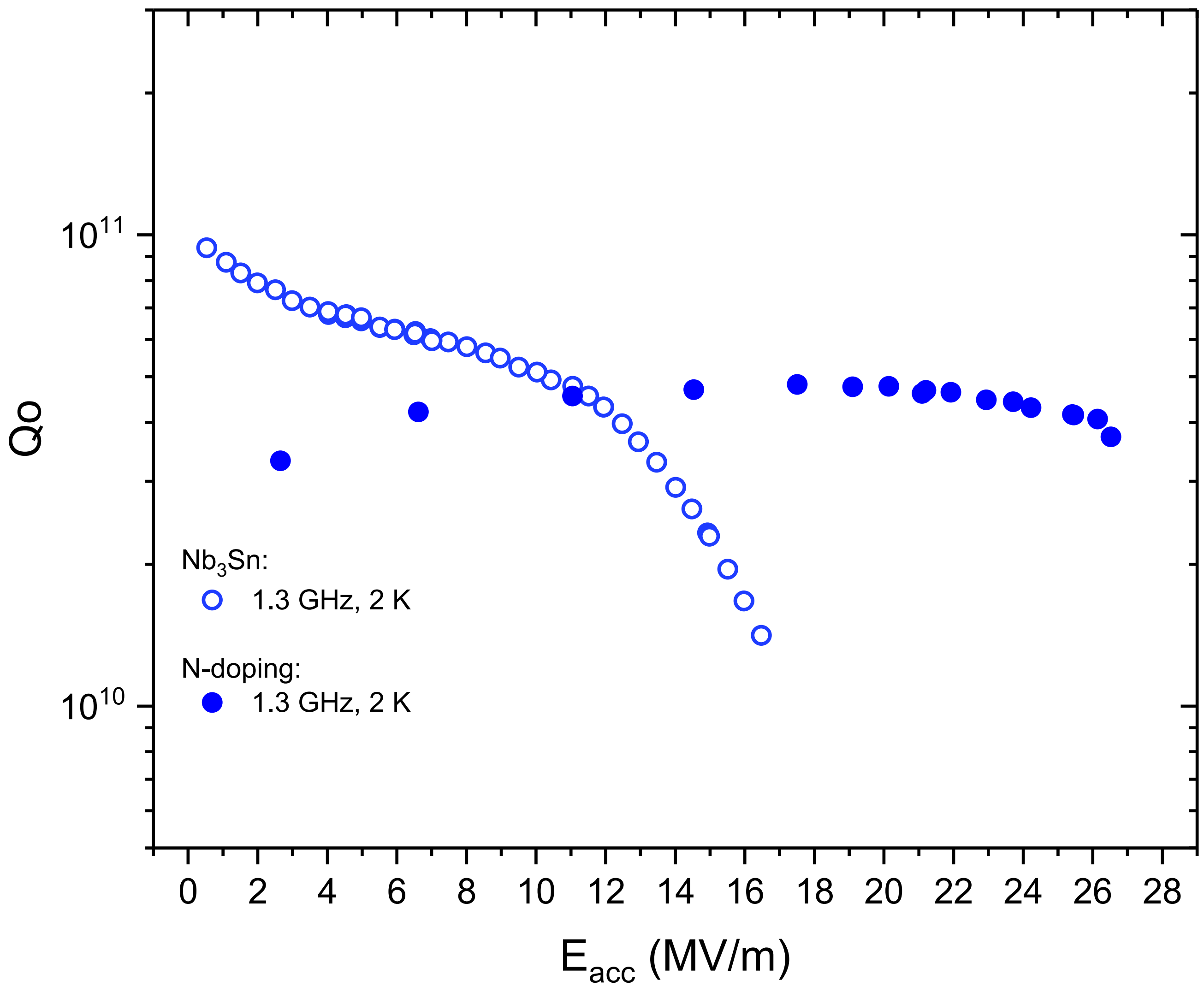
2 K Comparison: N-doping vs Nb_3Sn



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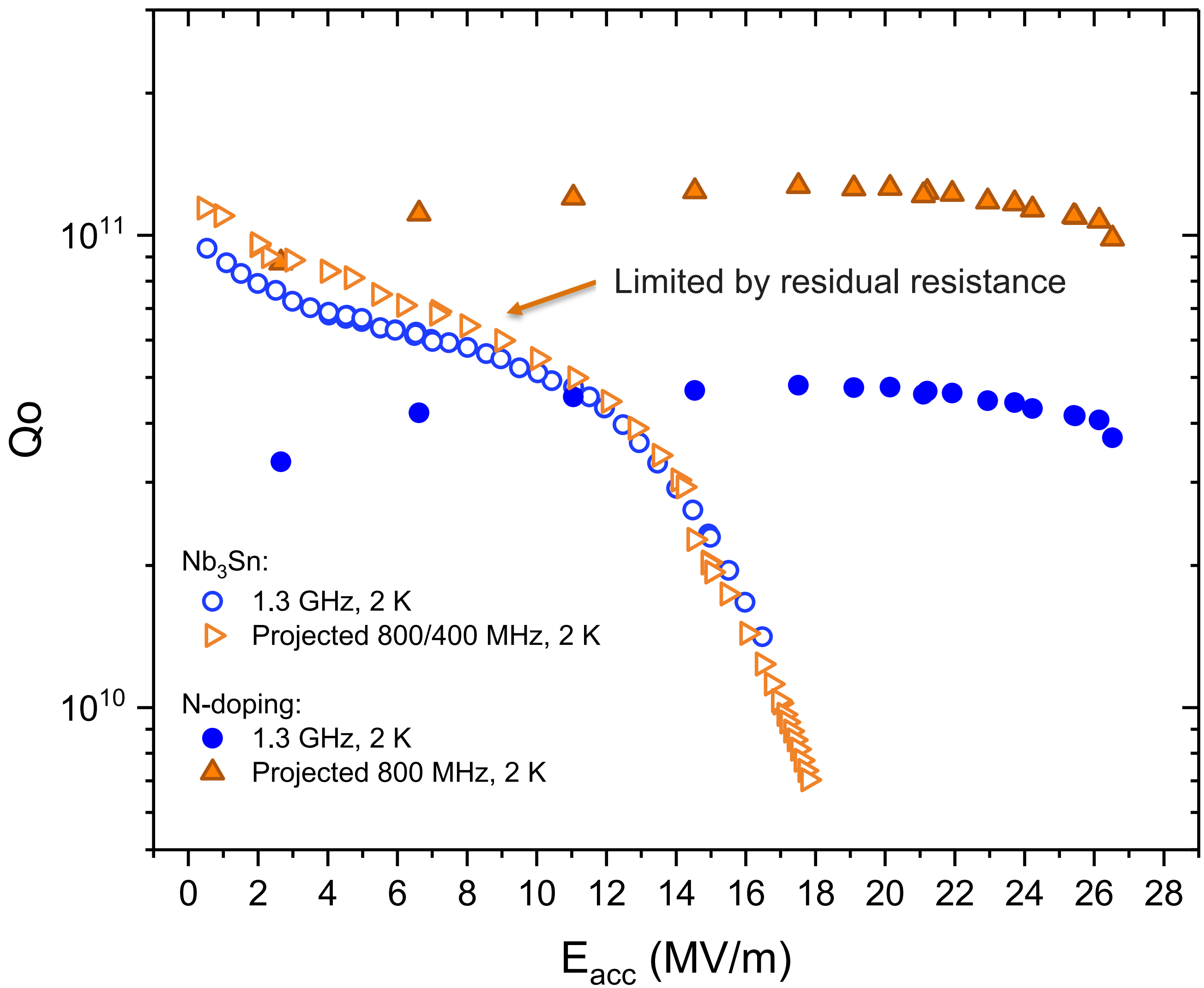

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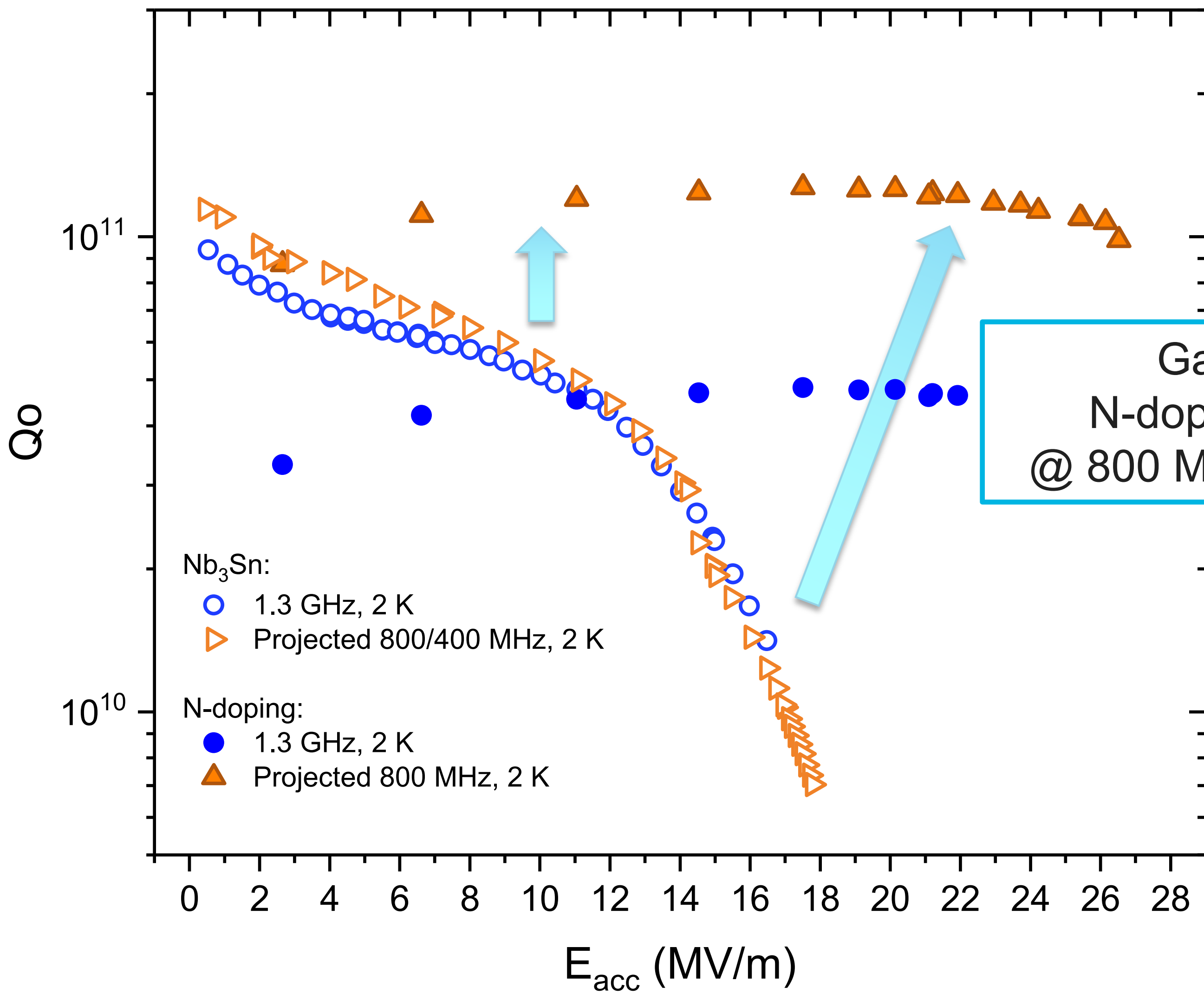

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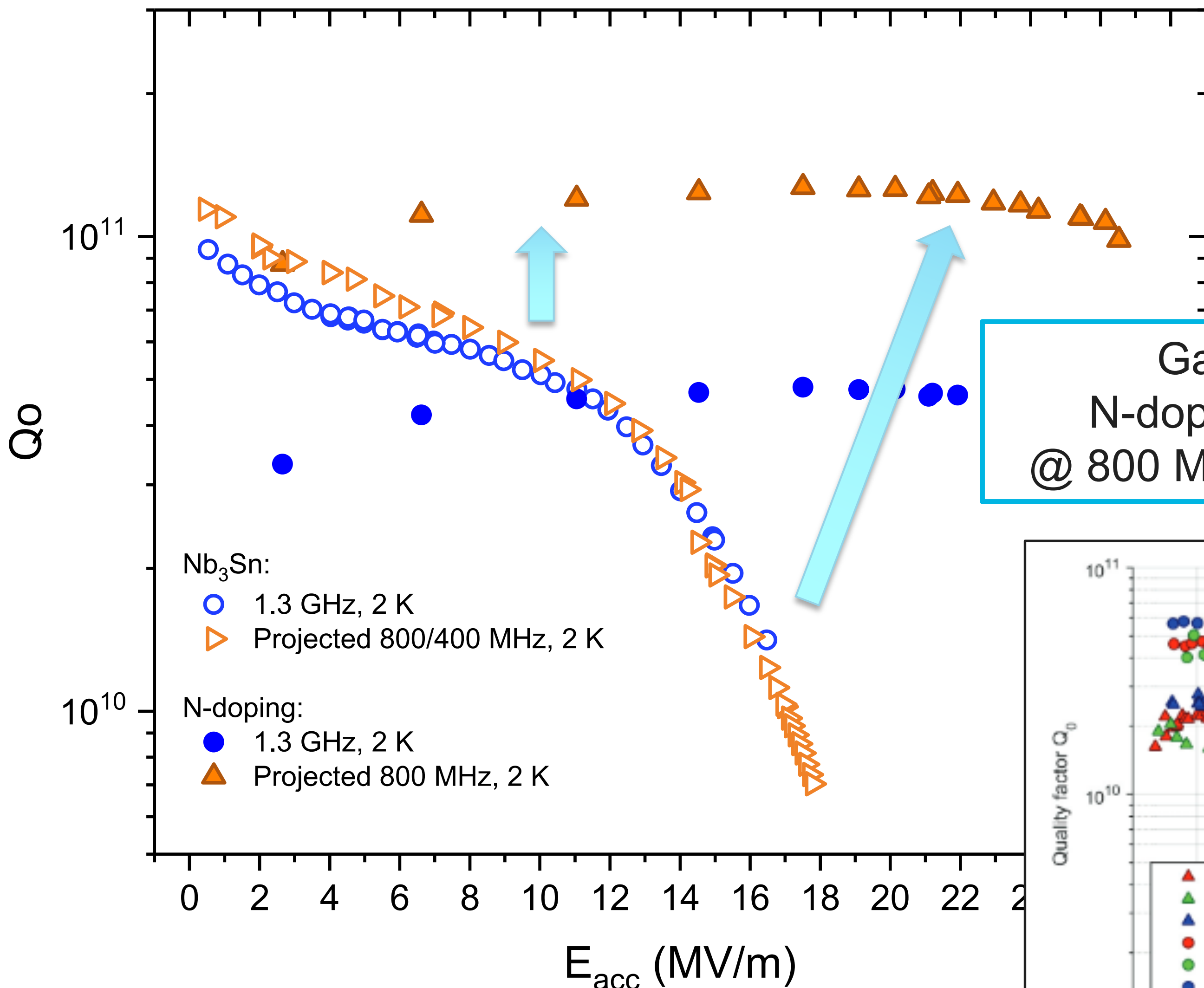

Gain given by
N-doping technology
@ 800 MV/m, 10-20 MV/m

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- Field dependence … not … ount
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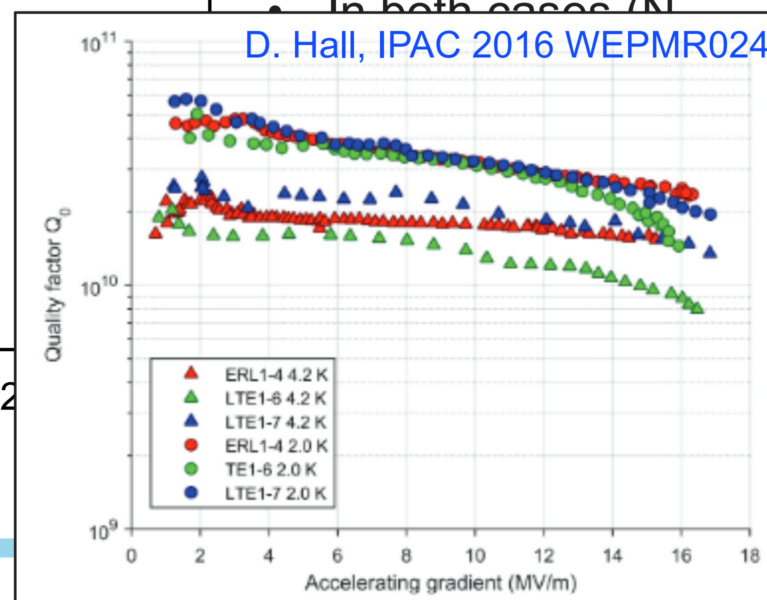

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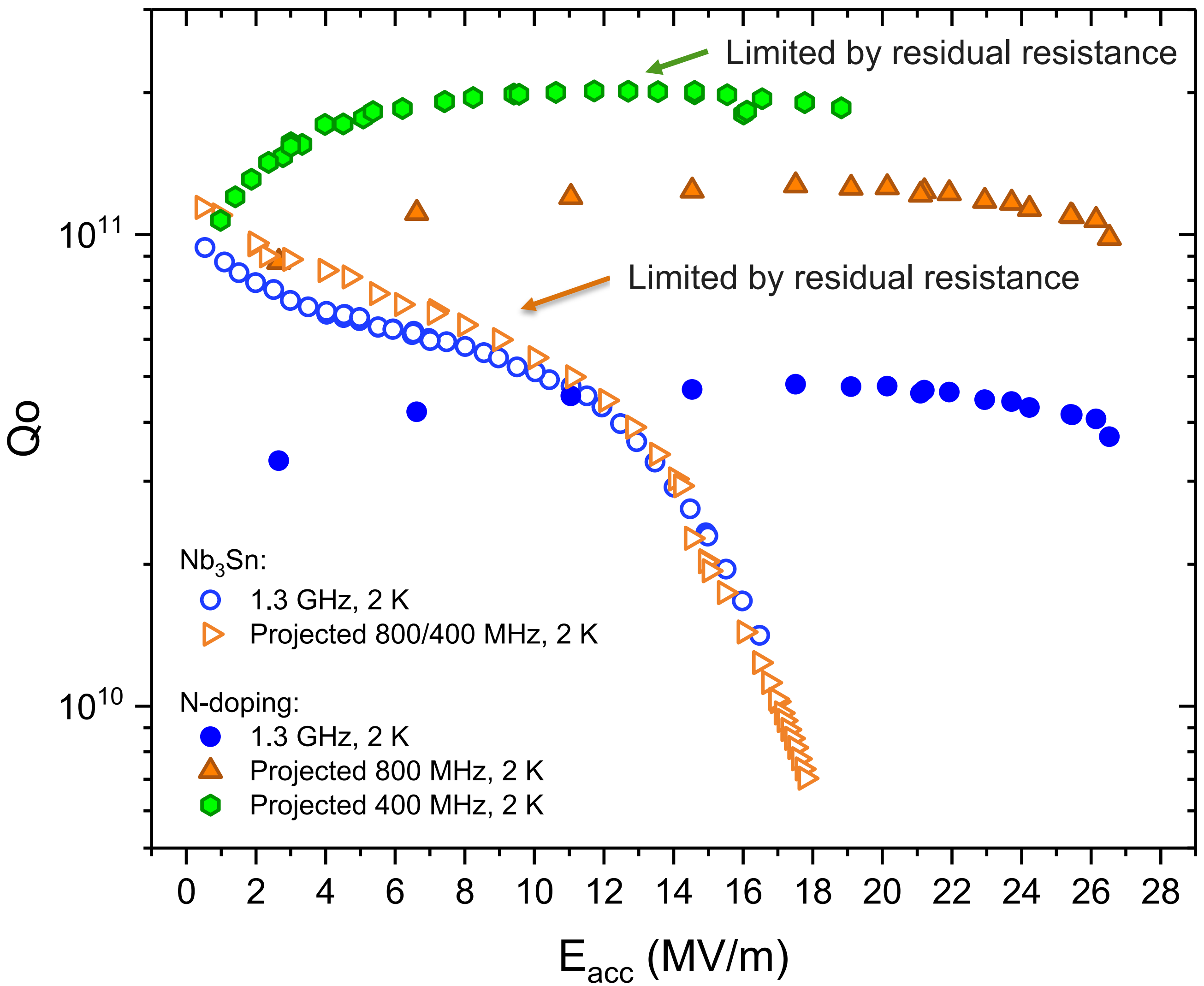

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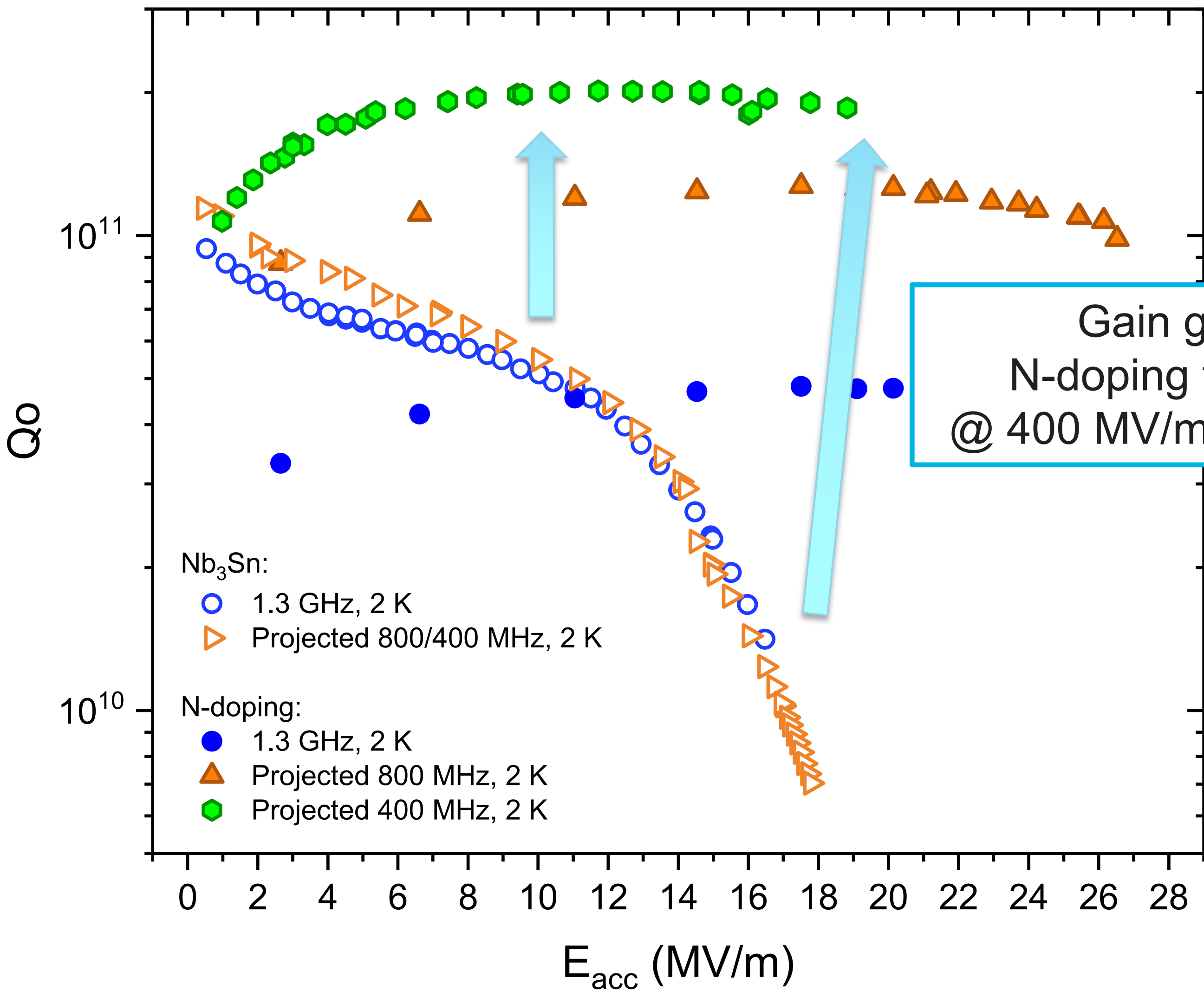

Gain given by
N-doping technology
@ 400 MV/m, 10-20 MV/m

WARNING:
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Summary on SRF technology for FCC

Technology comparison for FCC-ee (400/800 MHz SRF Nb cavities):

- N-doping: high-Q at medium field
  - Best technology for 2 K operation
  - Suitable for operation at 10 and 20 MV/m
  - Mature technology already applied to cryomodules production and fully transferred to industry

- Nb_3Sn: higher Tc
  - Best technology for 4.5 K operation at 10 MV/m
  - Need to improve quench field to be suitable for operation at 20 MV/m (potential for operation at very high gradient → 80 MV/m)
  - Not yet implemented to cryomodules production

Conclusions

- N-infusion suitable for high-Q at high-gradient, studies focused on improving reliability → possible technology for ILC cost reduction

- Frequency dependence studies suggest that:
  - high-frequencies cavities may be suitable for high-Q applications at medium- and high-gradients
  - low-frequencies cavities are more likely to be affected by "Q-slope issues" due to R_{BCS} increasing with field

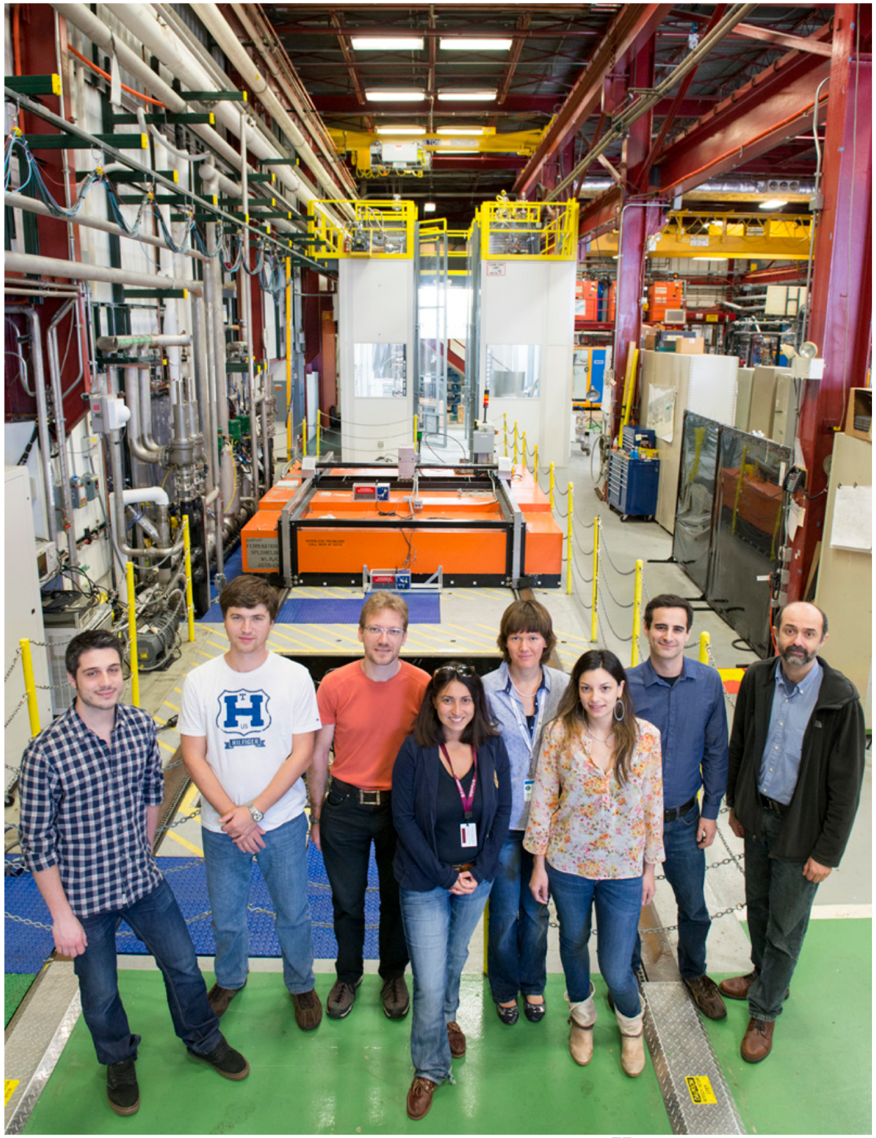
- Nb_3Sn shows promising results for 4.5 K operation (may be considered for FCC-ee) and potential for high-gradients

- N-doping is a mature technology and the current choice for 2 K operation at medium-gradients (may be considered for FCC-ee)

Team Effort

- Results shown here are due to many hardworking people

- Thanks to SRF measurement and research department for contributions with graphs, slides, etc.



Thank you for your attention!