RF tests of 1.3 GHz Nb/Cu elliptical cavities

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FCC Week 2022

31th of May 2022

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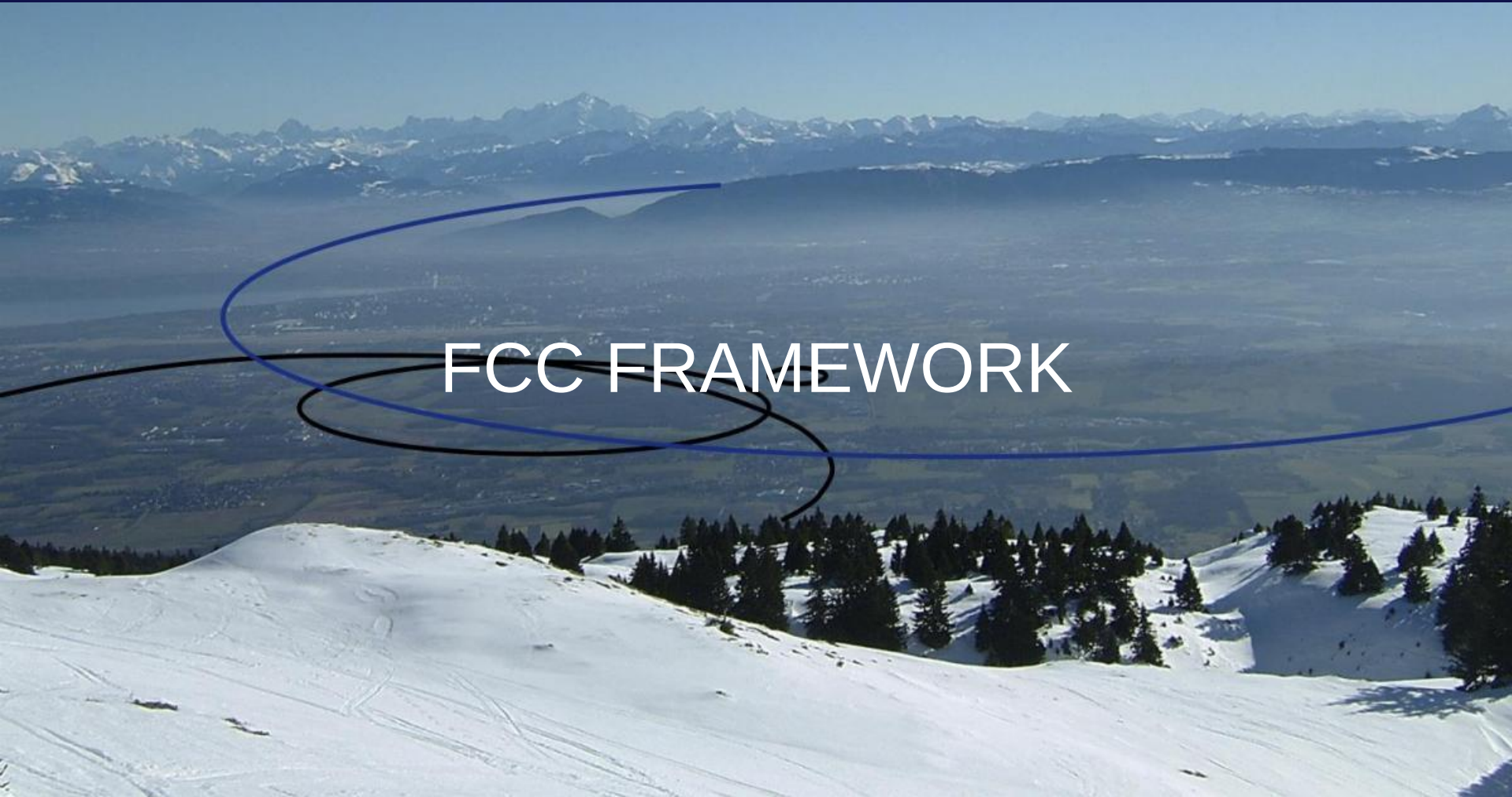

FCC FRAMEWORK

SRF System requirements

Evolved scenario from the CDR *(Input from WP1):*

23rd May 2022	Z		W		H		ttbar2		
	per beam	booster	per beam	booster	2 beams	booster	2 beams	2 beams	booster
Frequency [MHz]	400	800	400	800	400	800	400	800	800
RF voltage [MV]	120	140	1000	1000	2480	2480	2480	9190	11670
Eacc [MV/m]	5.72	6.23	11.91	24.26	11.82	25.45	11.82	24.52	25.11
# cell / cav	1	5	2	5	2	5	2	5	5
Vcavity [MV]	2.14	5.83	8.93	22.73	8.86	23.85	8.86	22.98	23.53
#cells	56	120	224	220	560	520	560	2000	2480
# cavities	56	24	112	44	280	104	280	400	496
# CM	14	6	28	11	70	26	70	100	124
T operation [K]	4.5	2	4.5	2	4.5	2	4.5	2	2
dyn losses/cav [W]	19	0.5	174	7	171	8	171	51	8
stat losses/cav [W]	8	8	8	8	8	8	8	8	8
Qext	6.6E+04	3.2E+05	1.2E+06	8.9E+06	1.5E+06	1.2E+07	1.8E+07	4.4E+06	5.3E+07
Detuning [kHz]	8.939	4.393	0.430	0.115	0.123	0.031	0.033	0.000	0.005
Pcav [kW]	880	205	440	112	352	95	29	230	20
rhob [m]	9937	9937	9937	9937	9937	9937	9937	9937	9937
Energy [GeV]	45.6	45.6	80.0	80.0	120.0	120.0	182.5		182.5
energy loss [MV]	38.49	38.49	364.63	364.63	1845.94	1845.94	9875.14		9875.14
cos phi	0.32	0.27	0.36	0.36	0.74	0.74	0.33	1.00	0.85
Beam current [A]	1.280	0.128	0.135	0.0135	0.0534	0.005	0.010	0.010	0.001
Lacc [m]	0.375	0.937	0.749	0.937	0.749	0.937	0.749	0.937	0.937
#cav/CM	4	4	4	4	4	4	4	4	4
R/Q [ohm]	79	521	152.8	521	153	521	153	521	521
G [ohm]	196.20	273.20	196.34	273.20	196.34	273.20	196.34	273.20	273.20
Q0	3.0E+09	2.0E+10	3.0E+09	2.0E+10	3.0E+09	2.0E+10	3.0E+09	2.0E+10	2.0E+10
Ep/Eacc	1.90	2.00	2.05	2.00	2.05	2.00	2.05	2.00	2.00
Bp/Eacc	4.10	4.20	6.39	4.20	6.39	4.20	6.39	4.20	4.20
Ep [MV/m]	10.86	12.45	24.42	48.52	24.23	50.91	24.23	49.05	50.23
Bp [mT]	23.44	26.15	76.12	101.89	75.52	106.90	75.52	103.00	105.48
Cavity design	UROS1	UROS5	C3794	UROS5	C3794	UROS5	C3794	UROS5	UROS5

Most demanding scenario:

Frequency	**400 MHz**
E_{acc} [MV/m]	12
# cell/ cav	2
$T_{operation}$ [K]	4.5
Q_0	3E9

Timeline

Provide an optimized recipe for 400 MHz cavities fabrication

Delivery of FCC Feasibility Study

2021 | ***2022*** | ***2023*** | ***2024*** | ***2025***

400 MHz elliptical cavities

@400 MHz:
E_{acc}~12 MV/m
Q_0~3E9
T= 4.5 K

1.3 GHz elliptical cavities

@1.3 GHz:
E_{acc}~12 MV/m
Q_0~4E8
T= 4.2 K

Synergy (and co-funding) with general SRF R&D project

OVERVIEW OF 1.3 GHZ CAVITIES PROGRAM

Workflow

Substrates manufacturing

EN-MME, TE-VSC, collaborations with INFN/LNL, JLab…

Surface treatments + Coating

TE-VSC-SCC

1.5 week

Cleanroom assembly

SY-RF-SRF

1 day

RF testing

SY-RF-SRF, TE-CRG

1 week

Workflow

Substrates manufacturing

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1.5 week

Cleanroom assembly

SY-RF-SRF

1 day

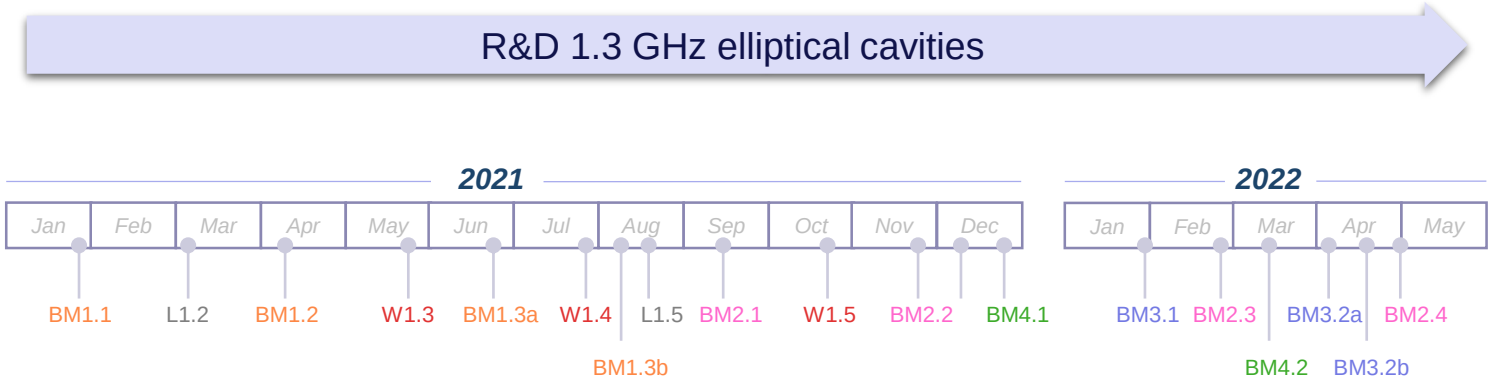
RF testing

SY-RF-SRF, TE-CRG

1 week

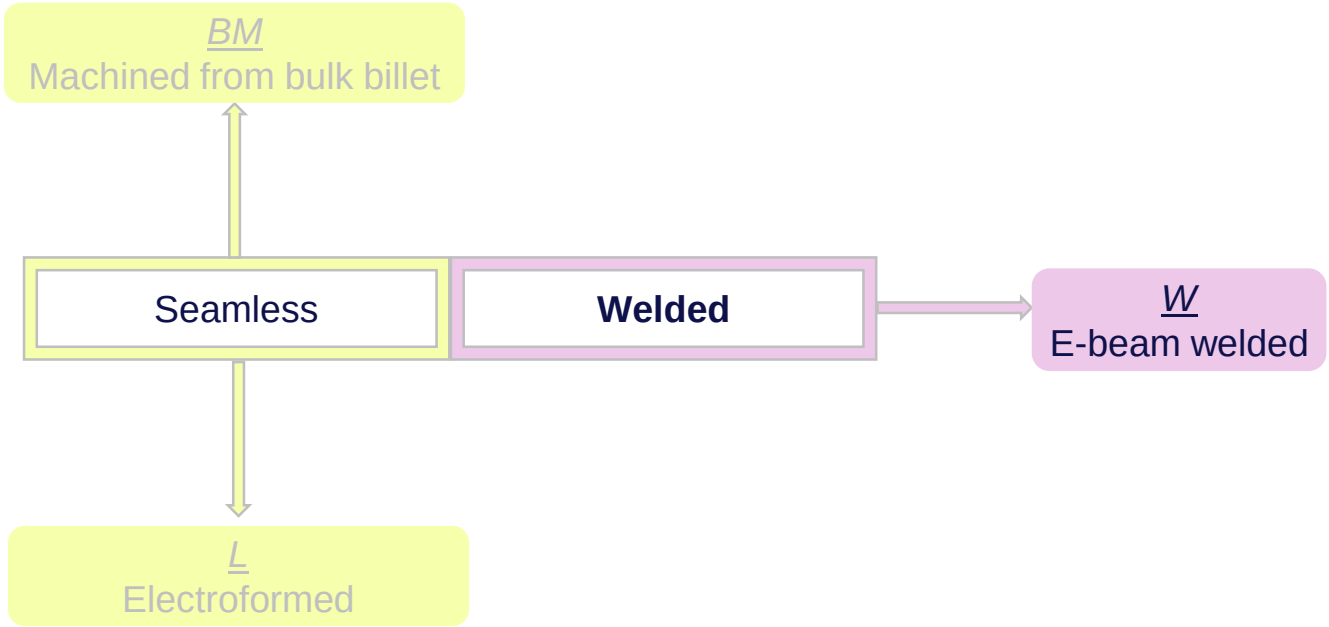
Regular meetings to comment results and establish a plan of action accordingly.

Tested cavities



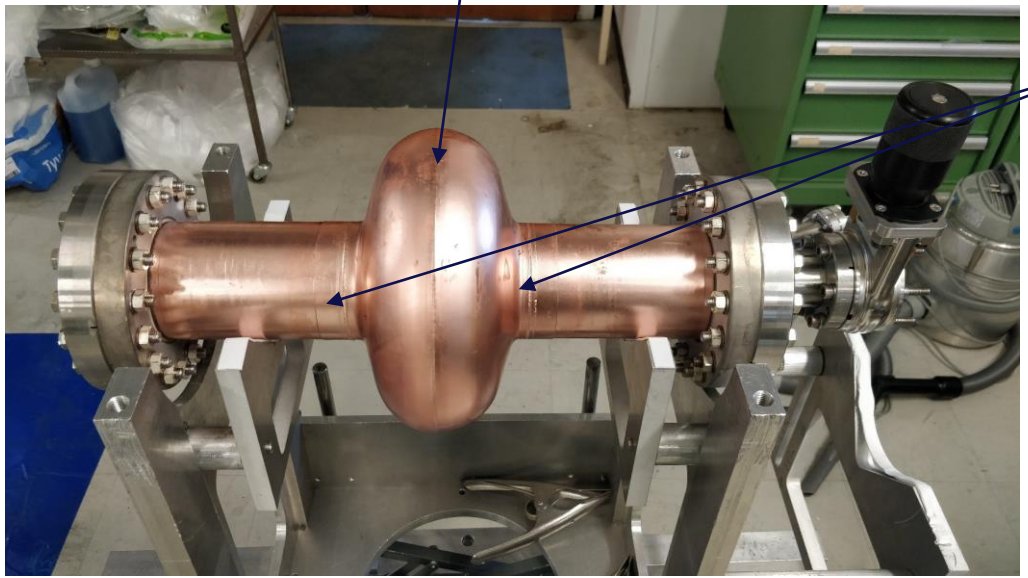
18 tests performed in the last 15 months thanks to the fruitful collaboration!

Tested cavities

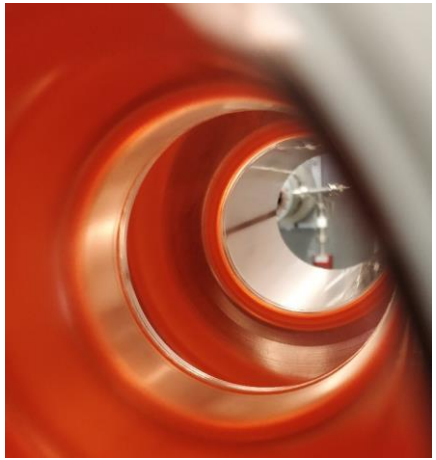


Tested cavities: Welded

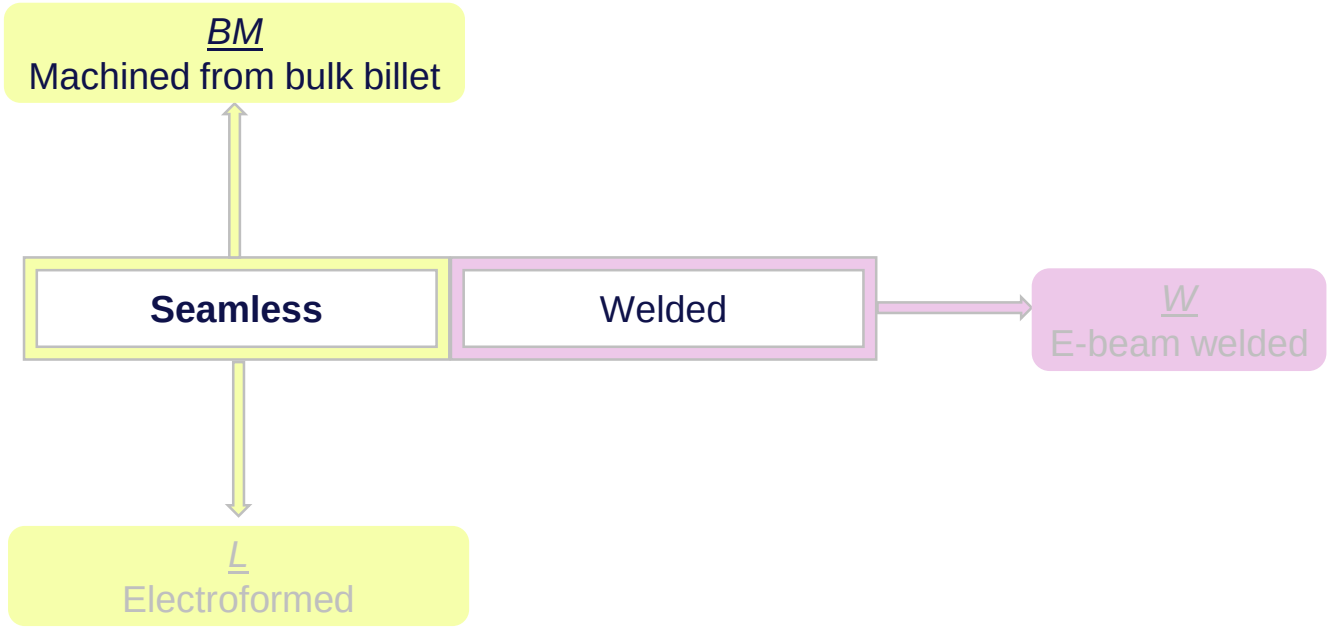
EQUATOR: E-beam welded from inside using a deflector



IRIS: Welded from inside by firing at a tilted angle from outside the cavity.



Tested cavities

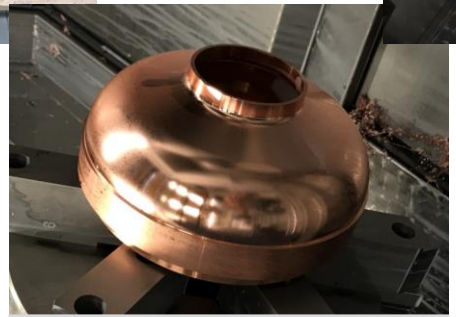


Tested cavities: Machined from bulk billet

Bulk Cu billet

Machining of second half cell

E-beam welded to cut-offs

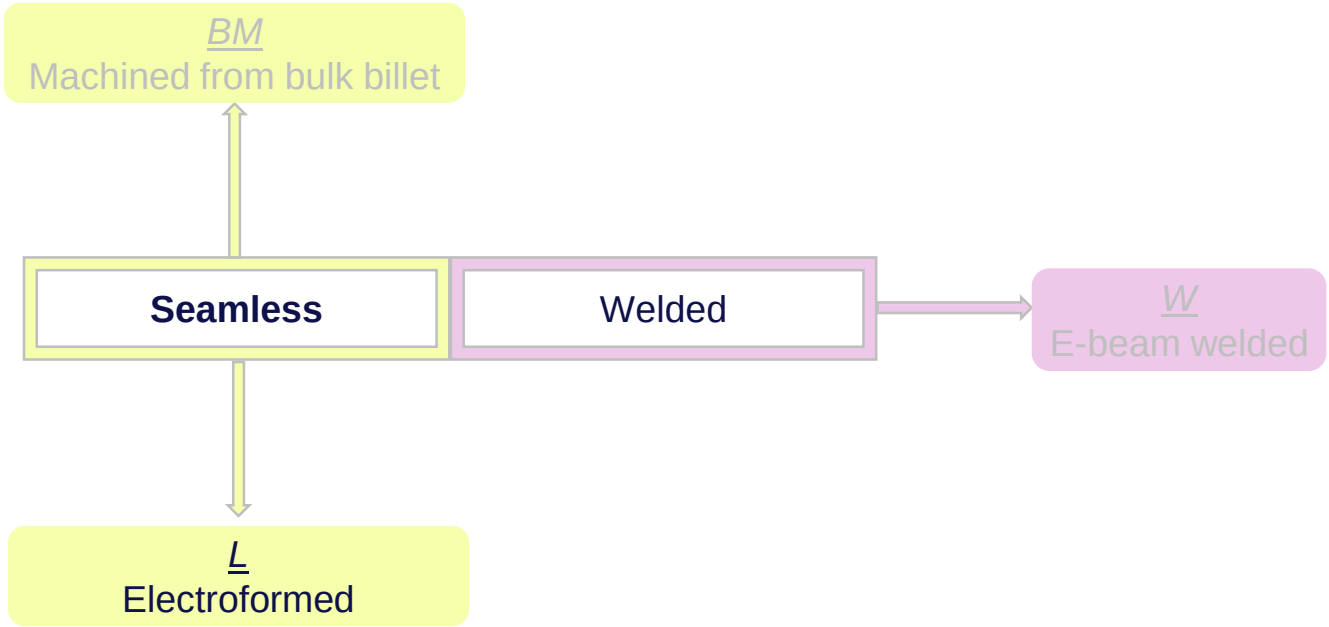


Machining of first half cell

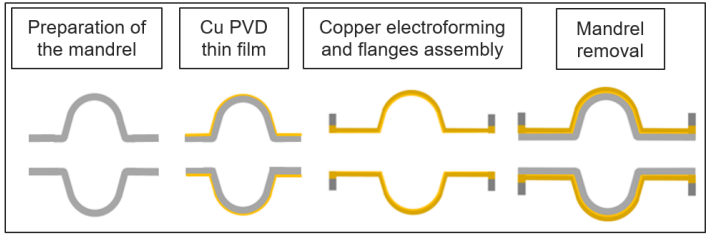
Machined cell

Courtesy: K. Scibor

Tested cavities



Tested cavities: Electroformed



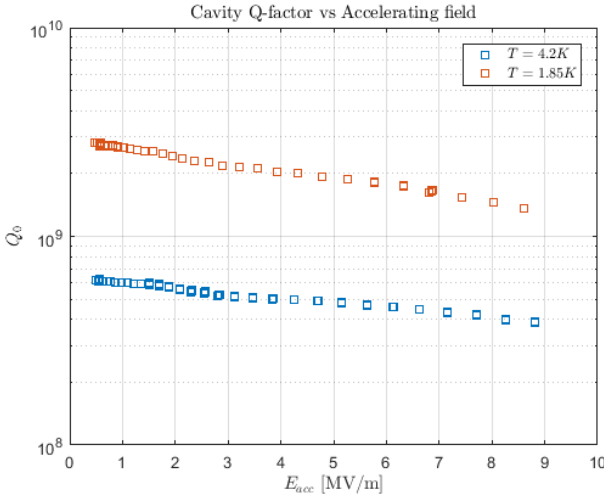
"L. Laín Amador. et al., "Electrodeposition of copper applied to the manufacture of seamless superconducting rf cavities ", Phys. Rev. Accel. Beams 24, 082002 ,2021

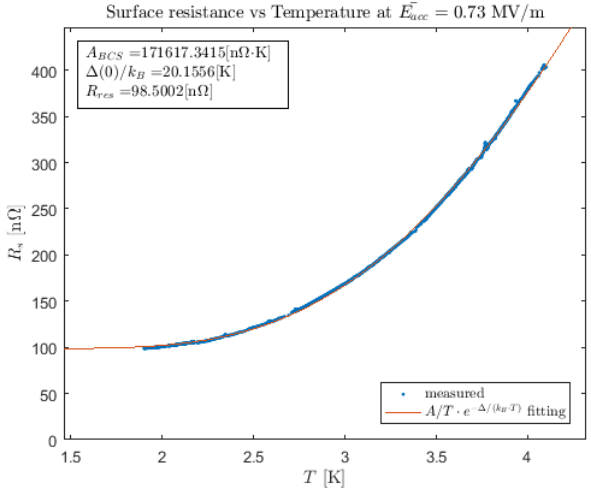
RF TESTS RESULTS

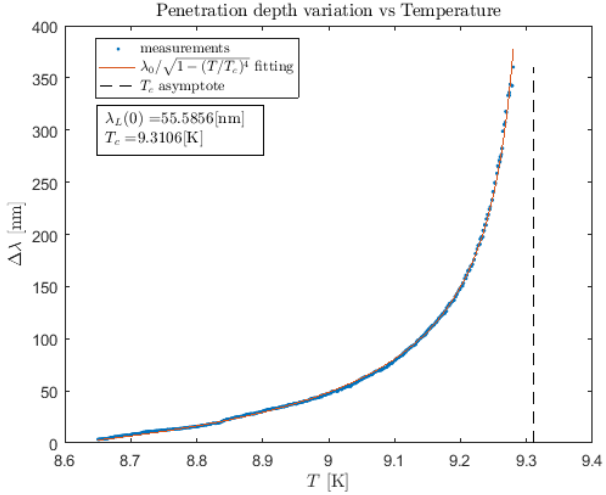
RF tests

1.3 GHz cavity testing campaign:

- ❑ Q vs E_{acc} at 1.85K and 4.2 K
- ❑ Q vs Temperature
- ❑ Frequency vs Temperature

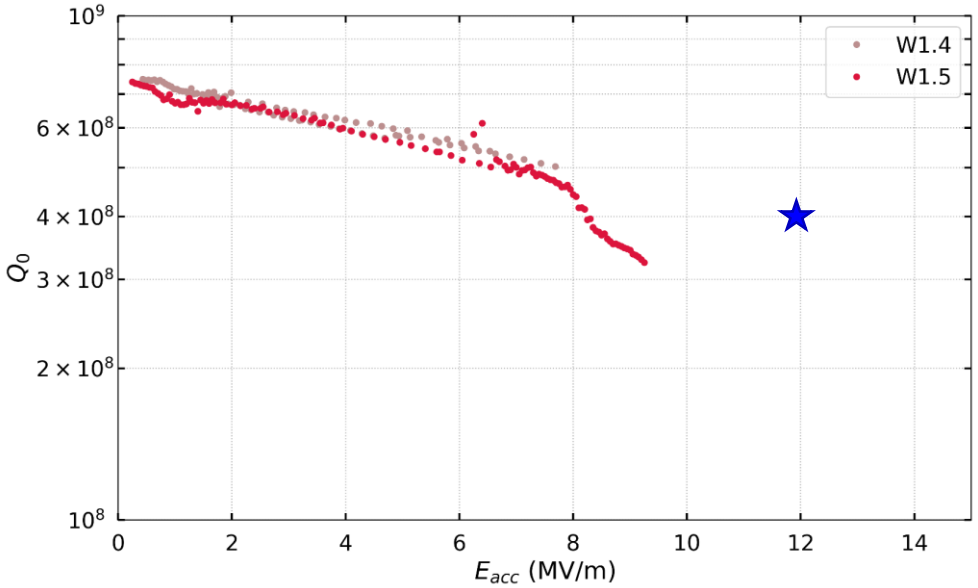






RF performance at 4.2 K

Welded → W
Internal e-beam welding

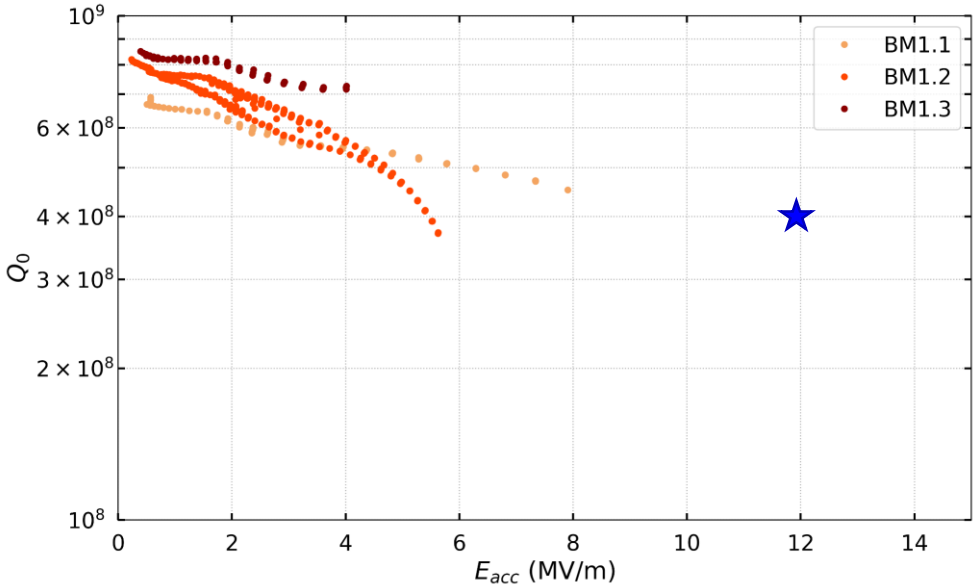


Remarks:

- W: 1 substrate tested. No big impact of weld on 4.5 K (BCS) performance, likely the higher probability of defects only affects $R_{residual}$.

RF performance at 4.2 K

Seamless → *BM*
Machined from bulk billet

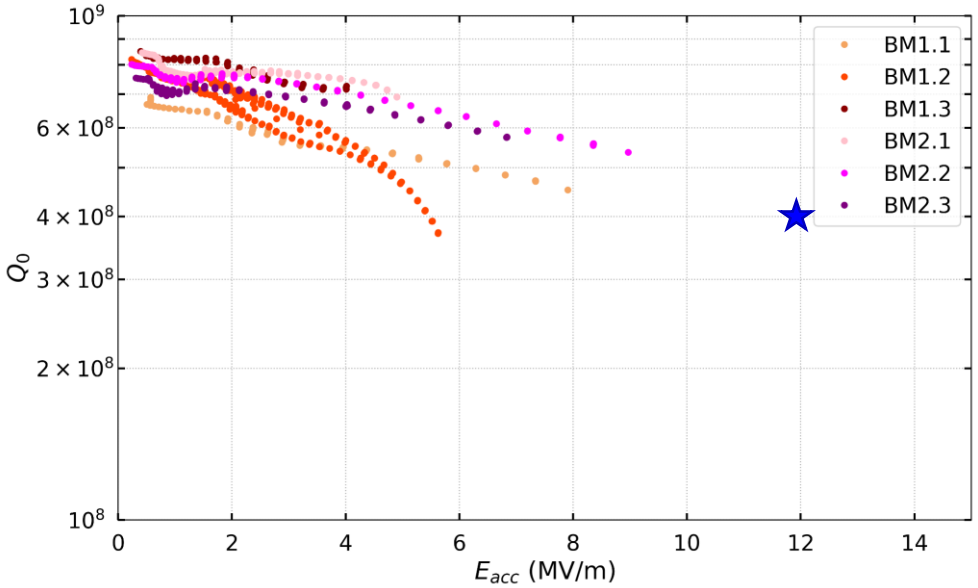


Remarks:

- BM: 4 substrates from different billets.
  - BM1: Last coating has record performance. Test stopped at low field at 4.2 K for safety.

RF performance at 4.2 K

Seamless → *BM*
Machined from bulk billet

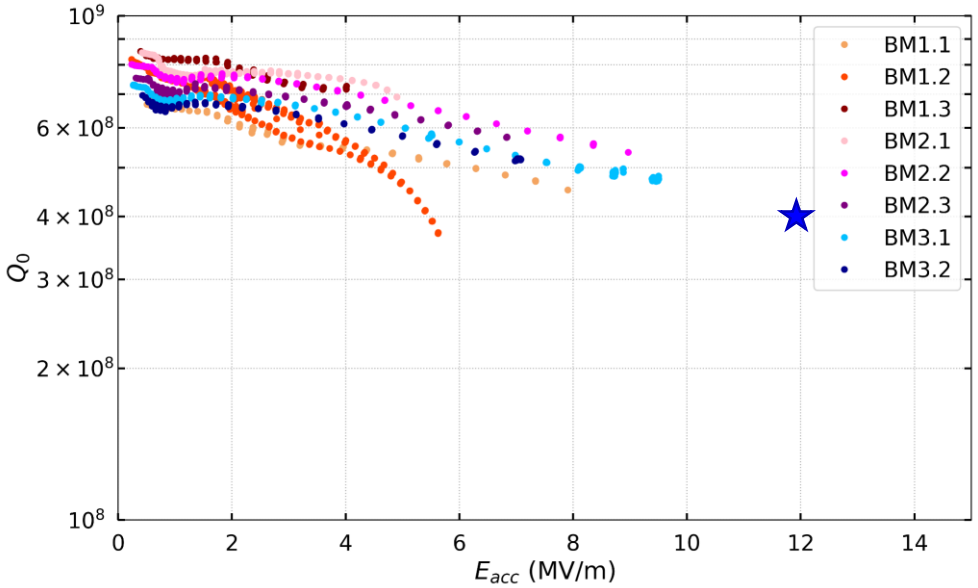


Remarks:

- BM: 4 substrates from different billets.
  - BM1: Last coating has record performance. Test stopped at low field at 4.2 K for safety.
  - BM2: Very similar performance achieved after re-coating.

RF performance at 4.2 K

Seamless → *BM*
Machined from bulk billet

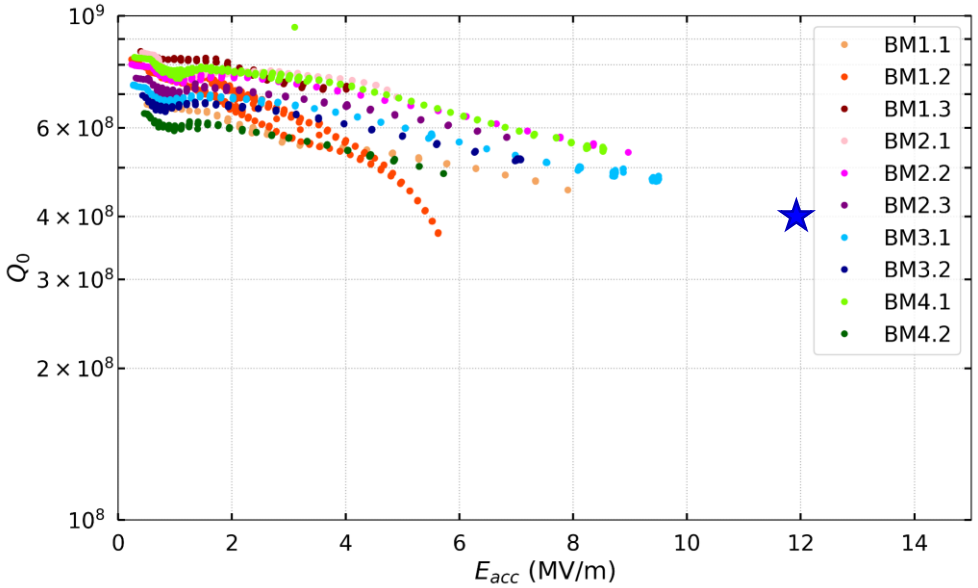


Remarks:

- BM: 4 substrates from different billets.
  - BM1: Last coating has record performance. Test stopped at low field at 4.2 K for safety.
  - BM2: Very similar performance achieved after re-coating.
  - BM3: Very similar performance achieved after re-coating.

RF performance at 4.2 K

Seamless → *BM*
Machined from bulk billet

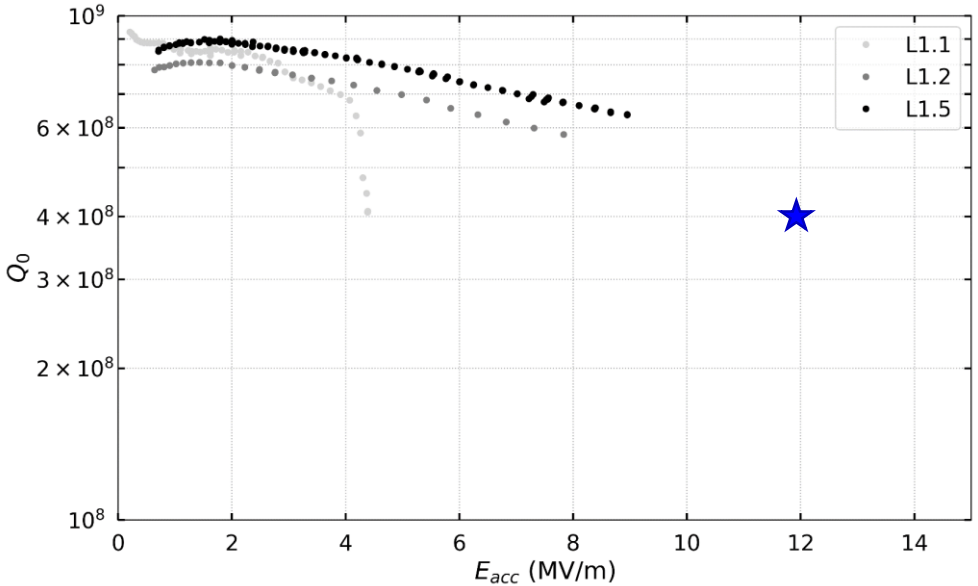


Remarks:

- BM: 4 substrates from different billets.
  - BM1: Last coating has record performance. Test stopped at low field at 4.2 K for safety.
  - BM2: Very similar performance achieved after re-coating.
  - BM3: Very similar performance achieved after re-coating.
  - BM4: Second coating worse due to issues during assembly.

RF performance at 4.2 K

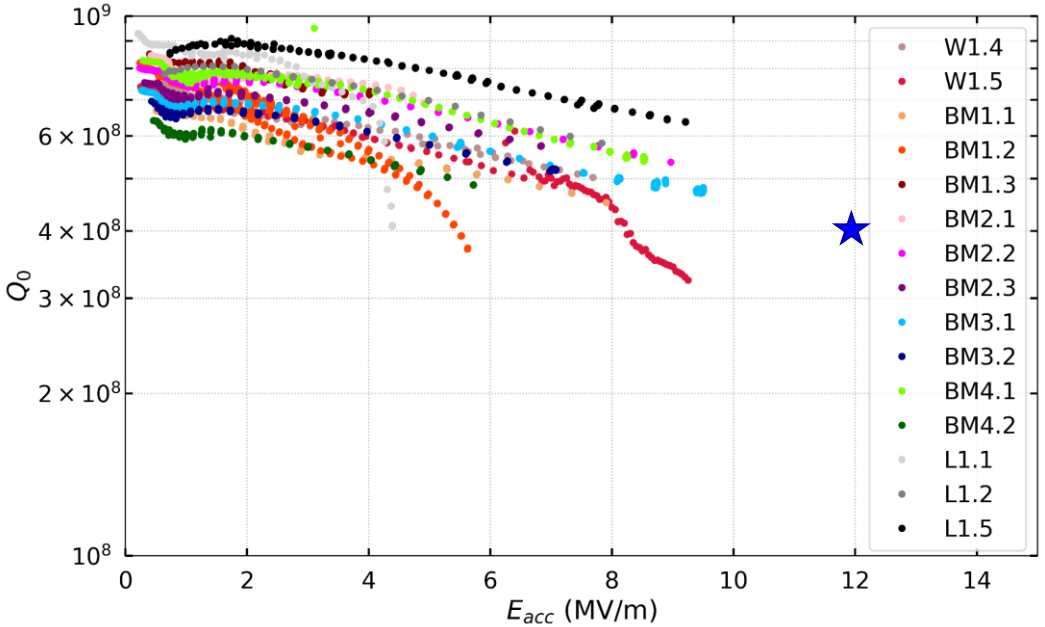
Seamless → *L* Electroformed



Remarks:

- L: 1 substrate produced. Peel-off during 1st coating. Very promising results of 2nd and 3rd coatings at 4.5 K.

RF performance at 4.2 K



Conclusions:

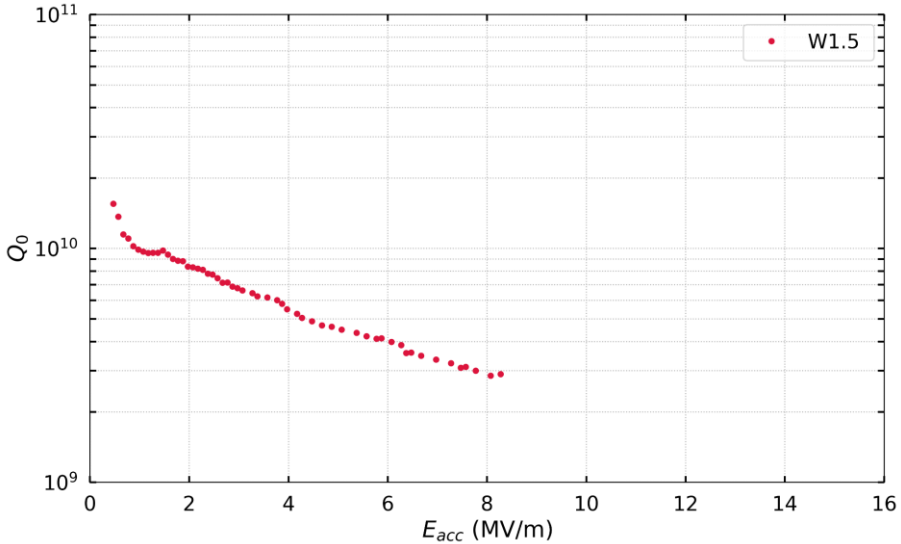
- BCS resistance has been optimized.
- **FCC** SRF requirements in terms of material properties are are potentially met with high repeatability using Nb/Cu technology.

Next steps:

- Scale HIPIMs on 400 MHz cavity substrates (starting now)
- Continue the R&D for optimizing this technology to use it in **high energy, high gradient accelerators (applications including FCC)**

RF performance at 1.85 K

Welded → *W* Internal e-beam welding

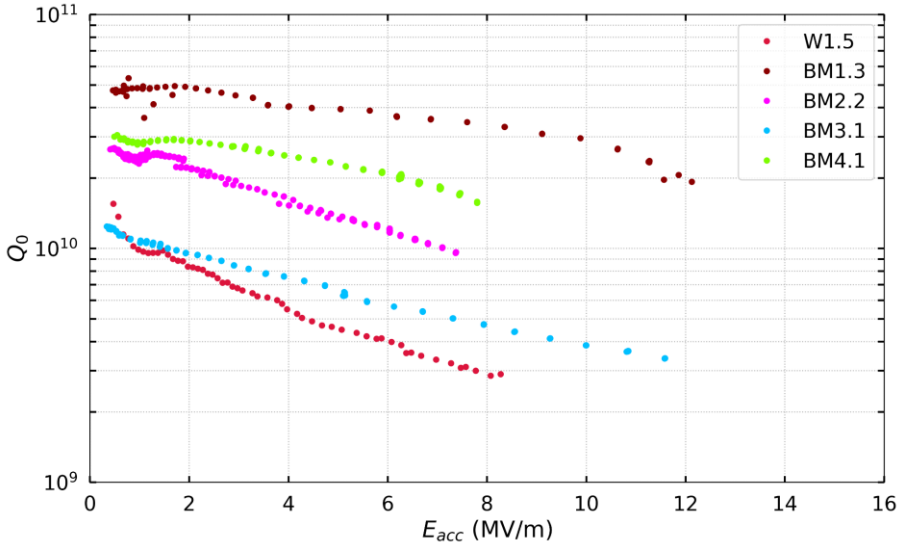


Remarks:

- W: Remarkable Q slope.

RF performance at 1.85 K

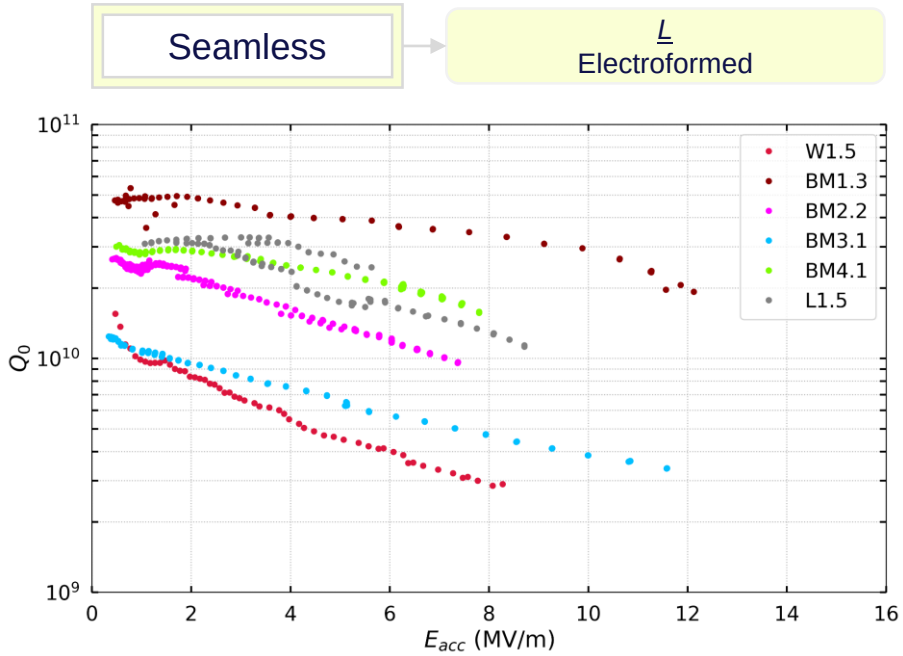
Seamless → *BM*: Machined from bulk billet



Remarks:

- W: Remarkable Q slope.
- BM: Very promising results, with BM1.3 showing record performance. Although same recipe has been followed to coat the cavities, this performance has not been achieved again. Currently under investigation.

RF performance at 1.85 K



Remarks:

- W: Remarkable Q slope.
- BM: Very promising results, with BM1.3 showing record performance. Although same recipe has been followed to coat the cavities, this performance has not been achieved again. Currently under investigation.
- L: Promising results obtained. More substrates are being produced.

RF performance at 1.85 K

Superconducting parameters

	BM1.1	BM1.2	BM1.3	BM2.1	BM2.2	BM2.3	BM3.1	BM3.2	BM4.1	BM4.2	W1.4	W1.5	N4.1	L1.1	L1.2	L1.5
R_{res} [nΩ]		19.99	4.48	14.4	7.34	15.09	26.4	22.45	7.82		19.53	16.4	10.4	33.27	23.9	8.7
Δ/k_B [K]		20.11	20.33	19.96	20.1	20.3	19.8	19.8	20.6		20.38	21.23	19.1	19.75	19.8	20.27
A_{BCS} [nΩ·K]		1.56E+05	1.46E+05	1.34E+05	1.55E+05	1.69E+05	1.52E+05	1.59E+05	1.71E+05		1.75E+05	1.98E+05	1.11E+05	1.40E+05	1.68E+05	1.74E+05
T_c [K]	9.31	9.31	9.31	9.36	9.36	9.4	9.38	9.41	9.37	9.41	9.38	9.3579	9.35	9.3602	9.34	9.35
λ_L [nm]	55.58	51.73	51.08	49.31	48.04	47.75	48.98	46.99	55.44	50.86	49.56	49.33	48.57	51.54	56.8	48.01

RF performance at 1.85 K

Superconducting parameters

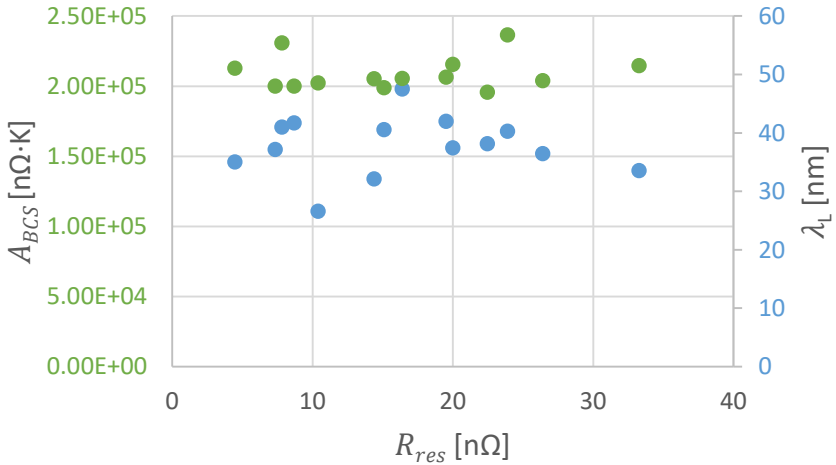
	Average	Standard deviation
R_{res} [nΩ]	16.44	8.01
Δ/k_B [K]	20.11	0.47
A_{BCS} [nΩ·K]	1.58E5	2.04E4
T_c [K]	9.36	0.03
λ_L [nm]	50.60	2.90

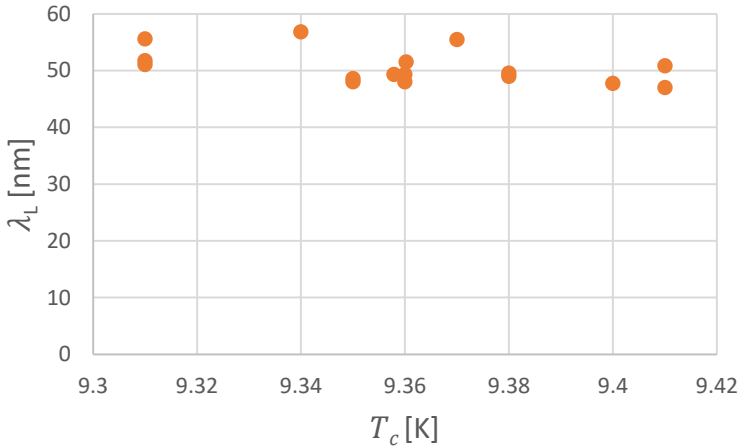
Remarks:

- Standard deviation of superconducting parameters is low: Reproducible coatings, process well under control.
- Residual resistance is more variable, which is expected as this parameter is influenced even by tiny defects.
- Correlation observed between Q slope and residual resistance.

RF performance at 1.85 K

Superconducting parameters





- A_{BCS} and λ_L are not dependent on the residual resistance.
- λ_L is not correlated to the transition temperature.

SUMMARY AND CONCLUSIONS

Summary and conclusions

- The R&D program on 1.3 GHz cavities is exploring the potential of the Nb/Cu technology on a high turnaround cavity substrate, which is recognized as international standard in the SRF community.
- An important goal is to provide a coating recipe for producing 400 MHz cavities that meet the FCC SRF system requirements.
- Different recipes have been investigated with a total of 18 cavities tested since 2021.
- The performance at 4.2 K (“BCS” resistance) has been optimized with high repeatability.
- RF results at 1.85 K are encouraging and ensure the potential application of this technology to high energy, high gradient accelerators.
- Repeatability of results at 1.85 K is however not yet achieved. Further investigations are ongoing to optimize the still occasionally occurring high residual resistance at 1.85 K, which includes a non linear component (Q-slope)

Thank you for your attention

Questions ?

Acknowledgements

Laetitia Dufay-Chanat, Zoran Jankovic, Serge Forel, Agostino Vacca, Torsten Koettig, Gabriel Pechaud, Sebastien Prunet