Review of SRF cavities developments towards FCC 800 MHz

CNRS/IN2P3/IJCLab Université Paris-Saclay

A. Miyazaki

Target gradient of SRF cavities for FCCee

12-May-23	Z		W		H			ttbar2	
	per beam	booster	per beam	booster	2 beams	booster	2 beams	2 beams	booster
RF Frequency [MHz]	400	800	400	800	400	800	400	800	800
RF voltage [MV]	120	140	1050	1050	2100	2100	2100	9200	11300
Eacc [MV/m]	5.72	6.23	10.61	20.01	10.61	20.76	10.61	20.12	20.10
# cell / cav	1	5	2	5	2	5	2	5	5
Vcavity [MV]	2.14	5.83	7.95	18.75	7.95	19.44	7.95	18.85	18.83
#cells	56	120	264	280	528	540	528	2440	3000
# cavities	56	24	132	56	264	108	264	488	600
# CM	14	6	33	14	66	27	66	122	150
+ #CM	14	6	33	8	0	13	0	122	123
- #CM			14				-	-	
T operation [K]	4.5	2	4.5	2	4.5	2	4.5	2	2
dyn losses/cav * [W]	19	0.3	129	3	129	4	129	23	3
stat losses/cav * [W]	8	8	8	8	8	8	8	8	8
Qext	5.8E+04	3.1E+05	9.2E+05	7.6E+06	9.1E+05	1.6E+07	4.5E+06	4.2E+06	8.1E+07
Detuning [kHz]	9.885	4.385	0.575	0.140	0.106	0.012	0.009	0.056	0.002
Pcav [kW]	901	210	378	89	382	47	78	163	8
energy loss / turn ** [MV]	39.40	39.40	370.00	370.00	1890.00	1890.00	10100.00		10100.00
cos phi	0.33	0.28	0.35	0.35	0.90	0.90	0.98	0.86	0.89
Beam current [A]	1.280	0.128	0.135	0.0135	0.0534	0.003	0.010	0.010	0.0005

* Heat loads from power coupler and HOM couplers not included
** Energy loss / turn from K. Oide table Jan. 19, 2023

Courtesy
F. Peauger

For 800 MHz: around **20 MV/m** in the machine

Machine ≠ target in production

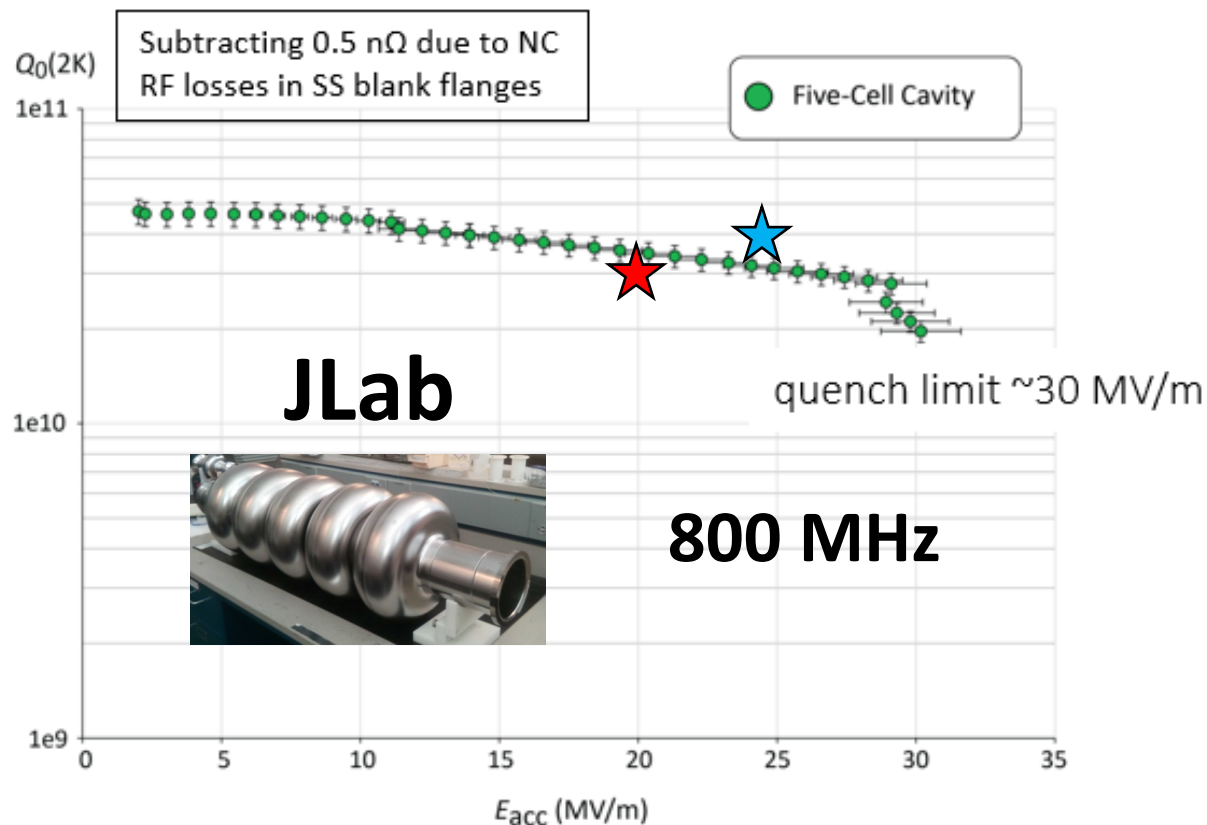| 12-May-23	Bare cavity in vertical test stand		Operation in the machine	
	Eacc (MV/m)	Q0	Eacc (MV/m)	Q0
1-cell 400 MHz	6.9	3.3E+09	5.7	2.7E+09
2-cell 400 MHz	13.2	3.3E+09	10.8	2.7E+09
5-cell 800 MHz	24.5	3.8E+10	20.0	3.0E+10

Courtesy
F. Peauger

- One needs safety margin in the acceptance test in vertical test stands (VT)
- Even the prototype does NOT fully meet the latest specification of VT
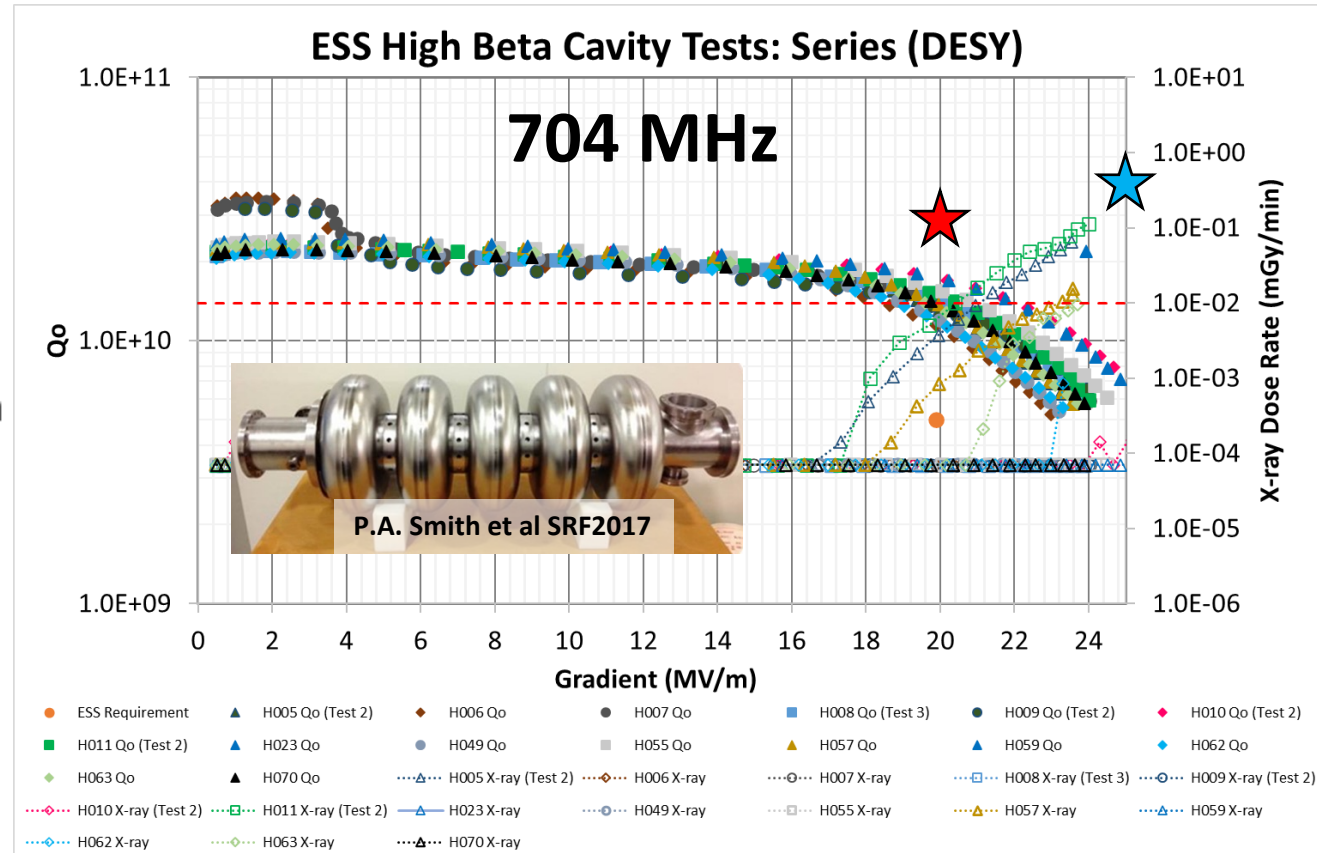- Production yield in mass production (?)

Prototype cavity (800 MHz)

quench limit ~30 MV/m

Courtesy
F. Marhauser
(Jlab)
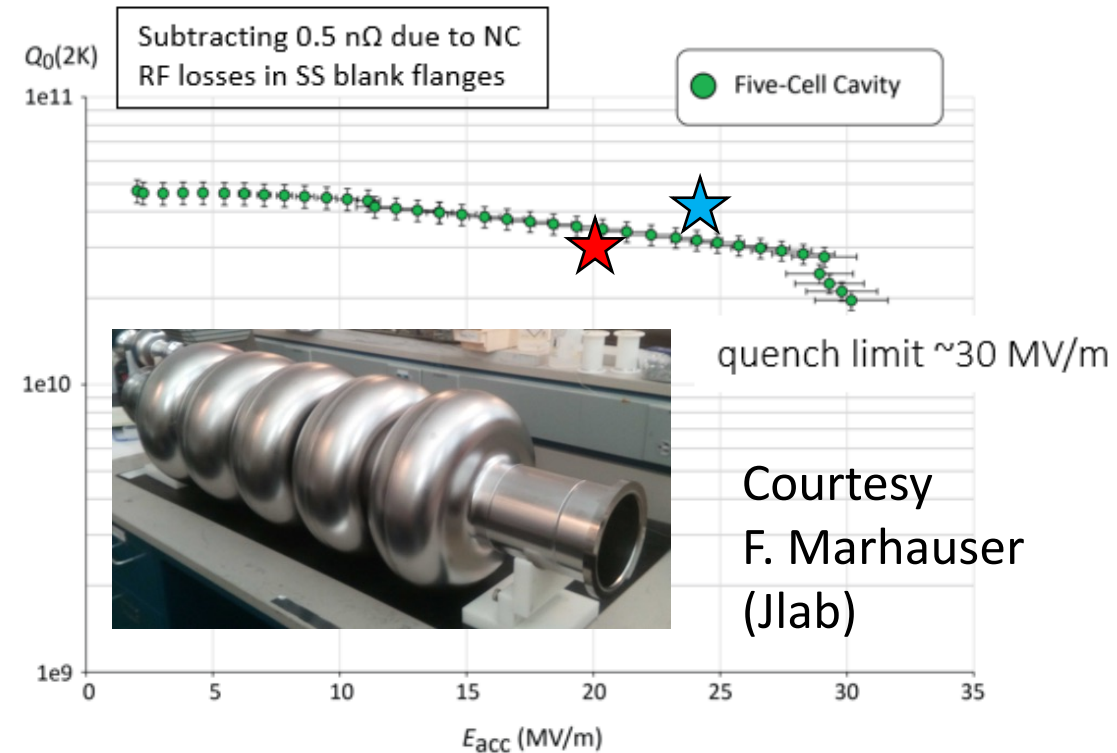
Performance limit:
- Quench at $E_{acc,max}$ = 31 MV/m
(B_{pk} ~ 130 mT) and Q_0 = 2e10

High-G/High-Q: prototype vs *series* production

Subtracting 0.5 nΩ due to NC RF losses in SS blank flanges

$Q_0(2K)$

● Five-Cell Cavity

JLab

quench limit ~30 MV/m

800 MHz

E_{acc} (MV/m)

ESS High Beta Cavity Tests: Series (DESY)

704 MHz

Q_0

X-ray Dose Rate (mGy/min)

Gradient (MV/m)

P.A. Smith et al SRF2017

Step	Amount
Bulk BCP	**200 um**
800C annealing	**3 hours**
Final EP	**30 um**
120C baking	**12 hours**

The ESS specification is conservative
→ Elecrtopolishing and baking were not mandatory

Step	Amount
Bulk BCP	**90+110 um**
600C annealing	**10 hours**
Final BCP	**20 um**

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FCC: comparison to other projects

- Highest demands on gradient out of non-1.3 GHz cavities
- **Highest demands on Q_0**

<u>We need state-of-the-art</u>
- Elecropolishing (EP)
- Baking/doping

in **industry**

P. Dhakal "Nitrogen doping and infusion in SRF cavities: A review" Phys Open 5 100034 2020
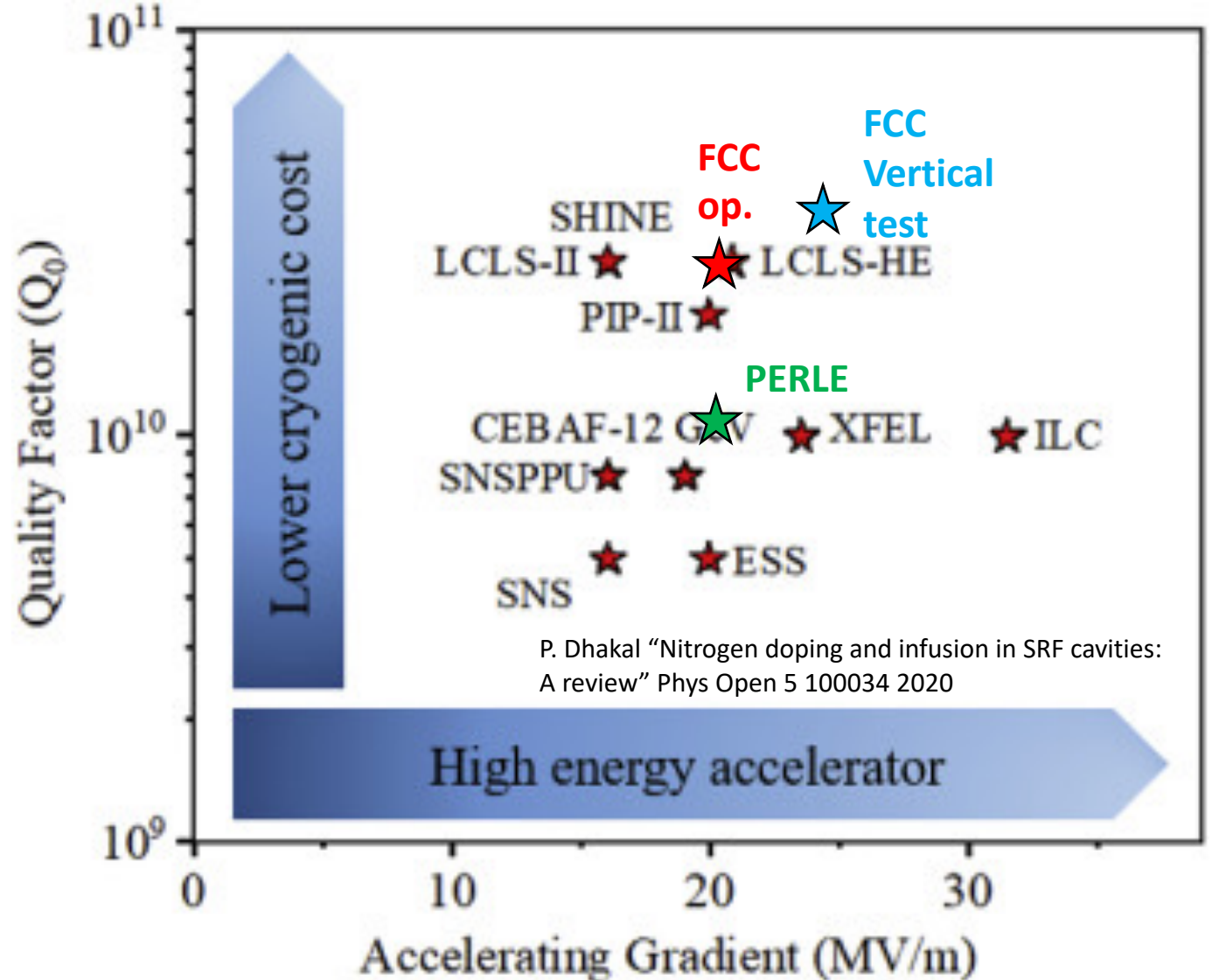
→ What can we learn from the 1.3 GHz projects?

1.3 GHz 9-cell cavities for LCLS-II-HE (Sep 2022)

D. Gonnella et al SRF2019

Step	Amount
Bulk EP1	200 um
900C or 950C annealing	3 hours
Bulk EP2	50 um
2N0 doping at 800C	2min/0min
Final EP	7 um

(hydrogen degassing and for flux expulsion)

(Original LCLS-II: 2N6 at 800C)

Anti-Q-slope in R_{BCS}

Q_0

Average quench gradient:
27.1±3.3 MV/m

J. Maniscalco TTC high-G/high-Q
WG meeting 09/08/2022

E_{acc} (MV/m)
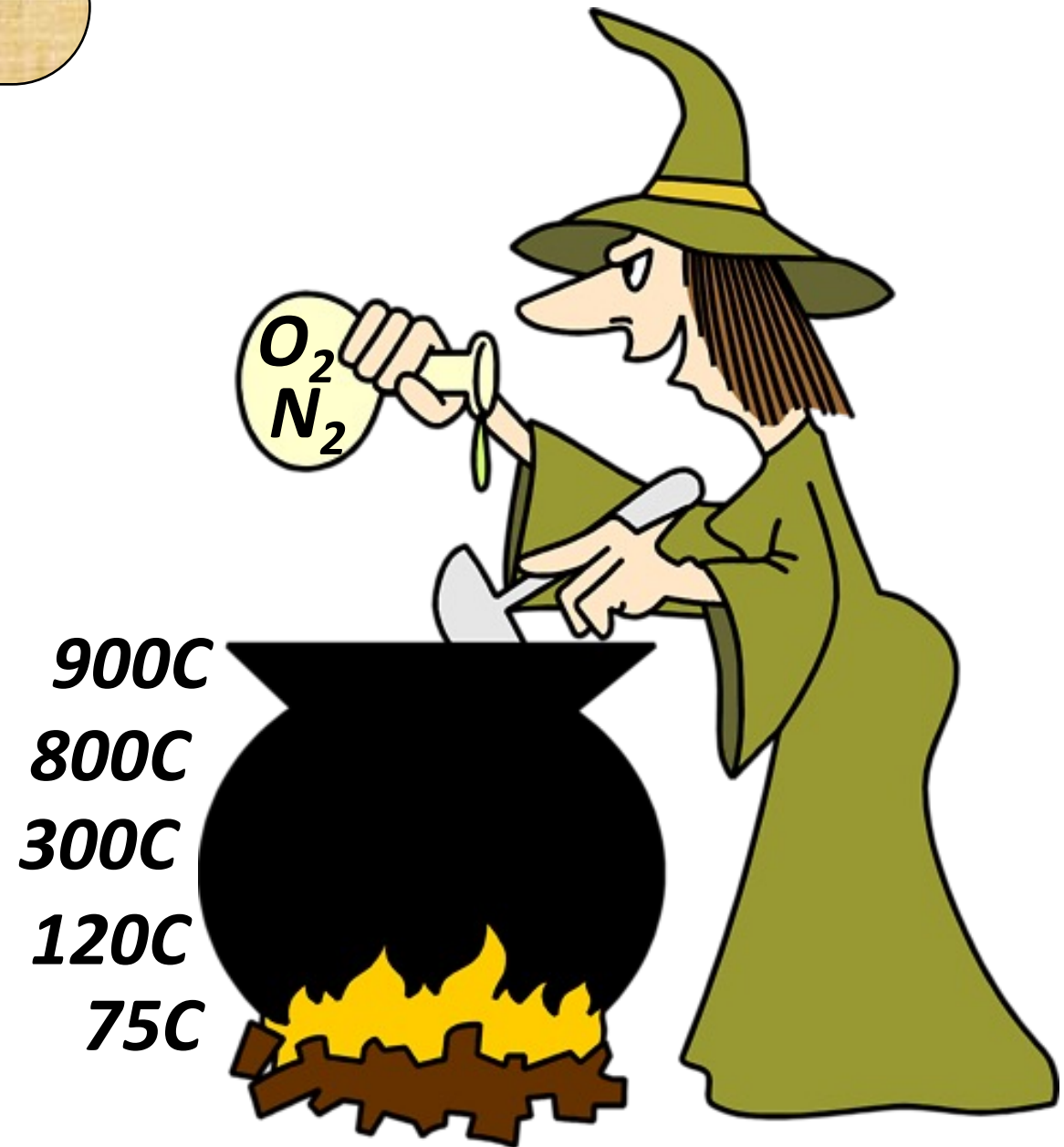
Average Q:
3.18±0.39×10^{10}

Cavities per bin

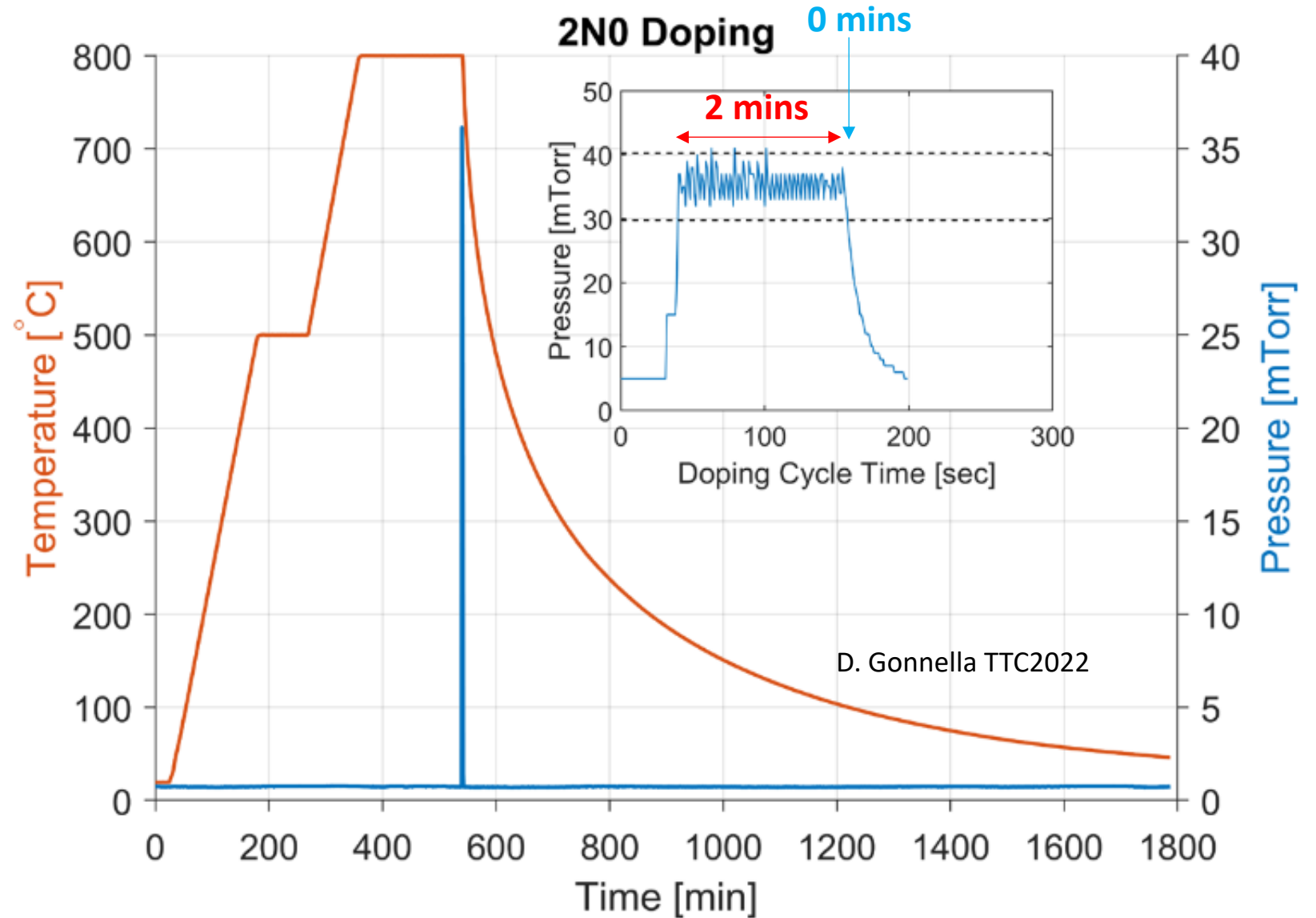$Q_0(21 \text{ MV/m})$
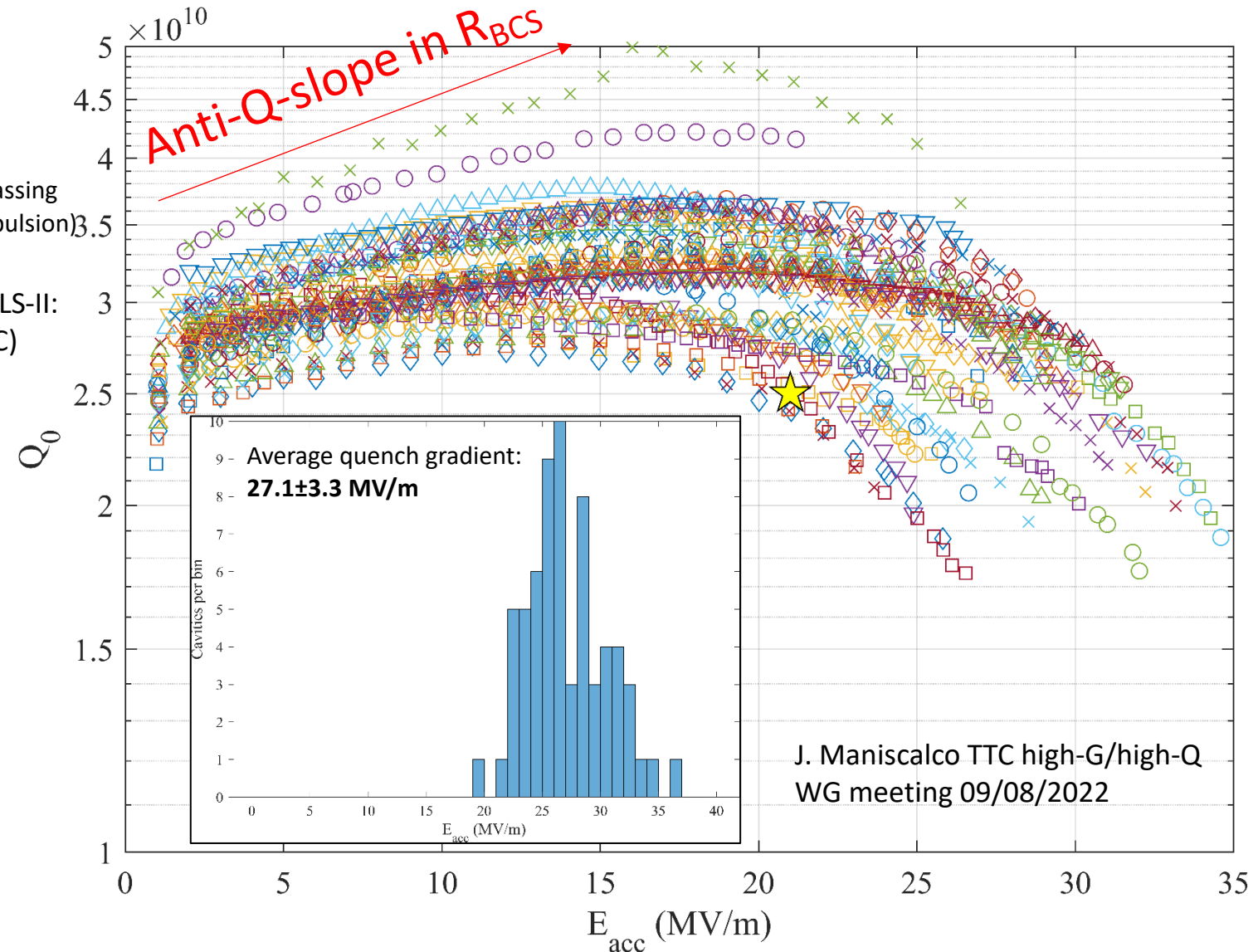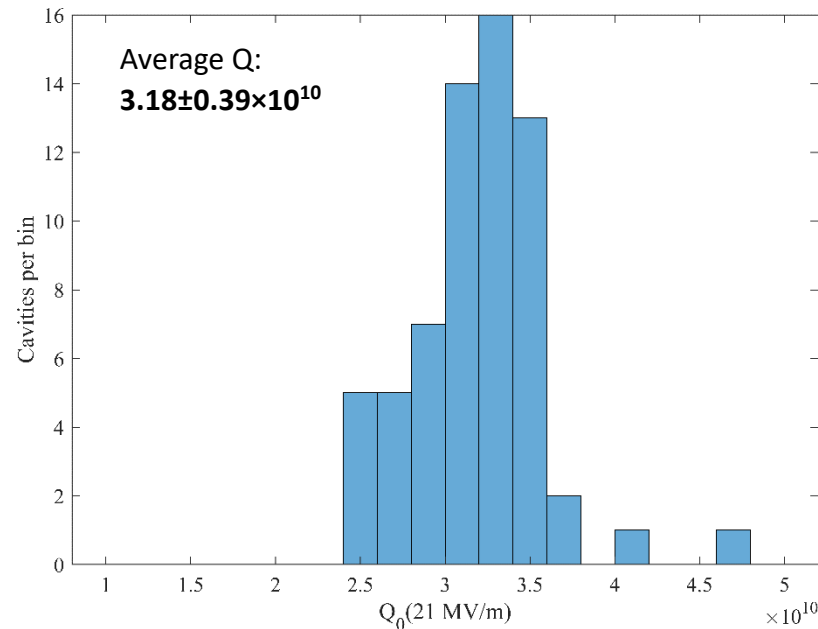
N-doping is successfully *industrialized* for 1.3 GHz

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Baking magic

- N-doping xNy
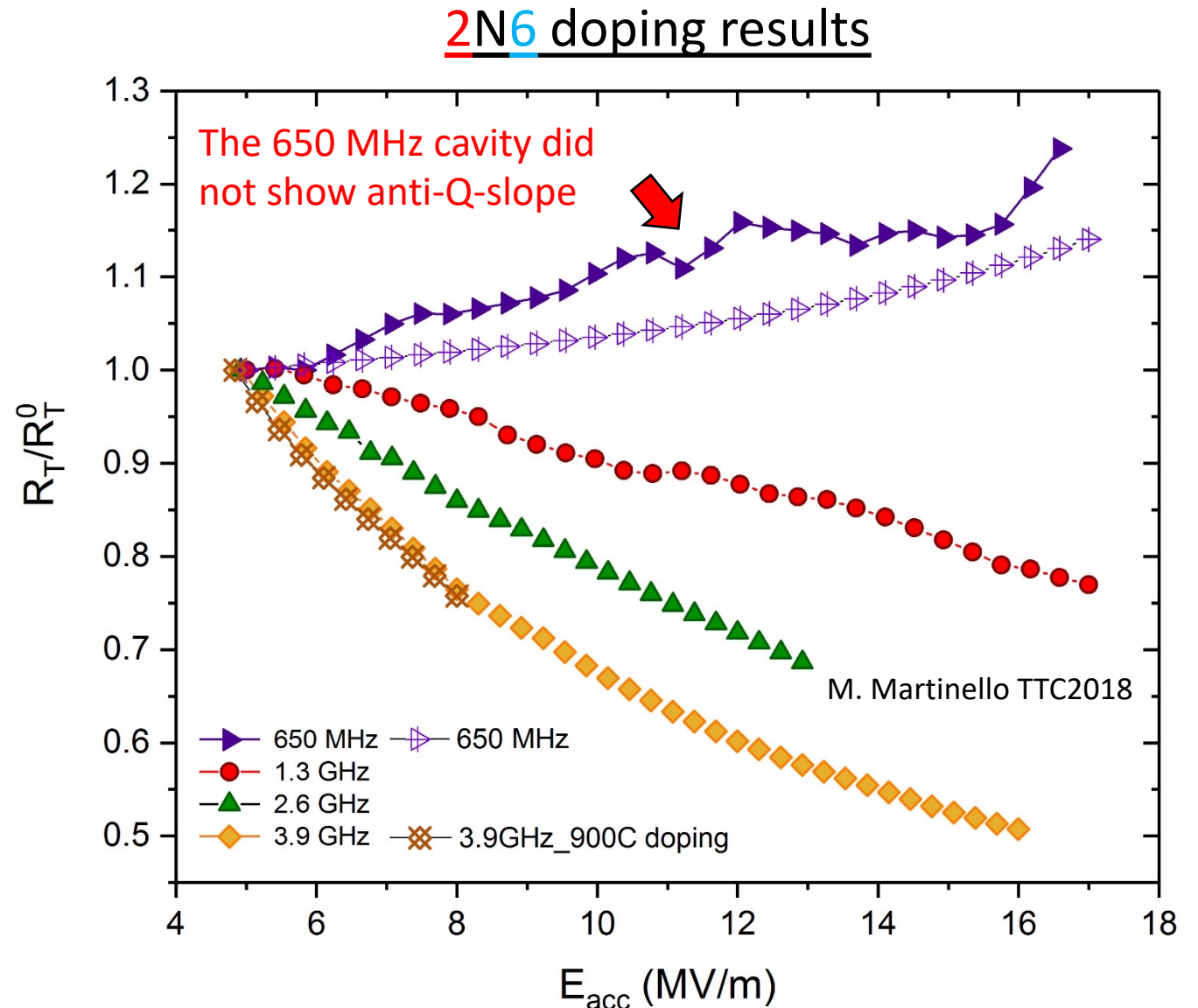- N-infusion
- 2-step baking
- Mid-T baking
- Low-T baking

O_2
N_2

900C
800C
300C
120C
75C

N-doping recipe

xNy doping

High temperature degassing 800 °C (~ 3hours) in UHV

↓

Nitrogen injection at the end of process (~ 25 mTorr) hold for 'x' mins

↓

Evacuate furnace and temperature hold for 'y' mins

↓

Furnace cooldown to room temperature in UHV

↓

Electropolishing (5-10 μm)

↓

High Pressure Rinse (HPR), clean room asselbly and rf test

D. Gonnella TTC2022

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P. Dhakal "Nitrogen doping and infusion in SRF cavities: A review" Phys Open 5 100034 2020
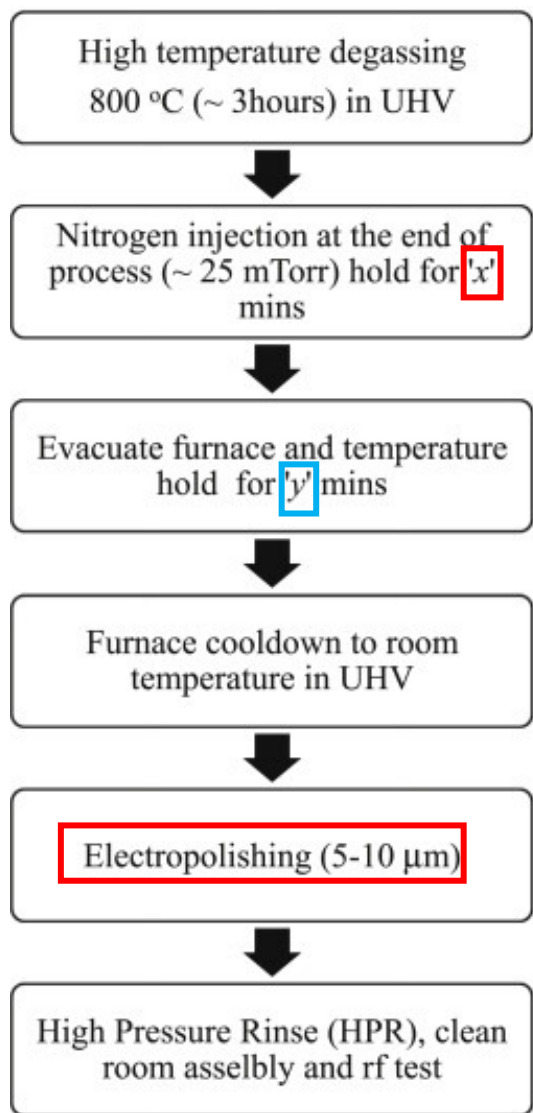
N-doping for lower frequency

- The characteristic **relative** increase of Q_0 (decrease in R_{BCS}) is usually not observed in cavities with below 1 GHz

→ Speculations on nonequilibrium physics as a function of frequency

- However, the **absolute** values on R_{BCS} and R_{res} may be improved by different baking/doping recipes even for low frequency cavities
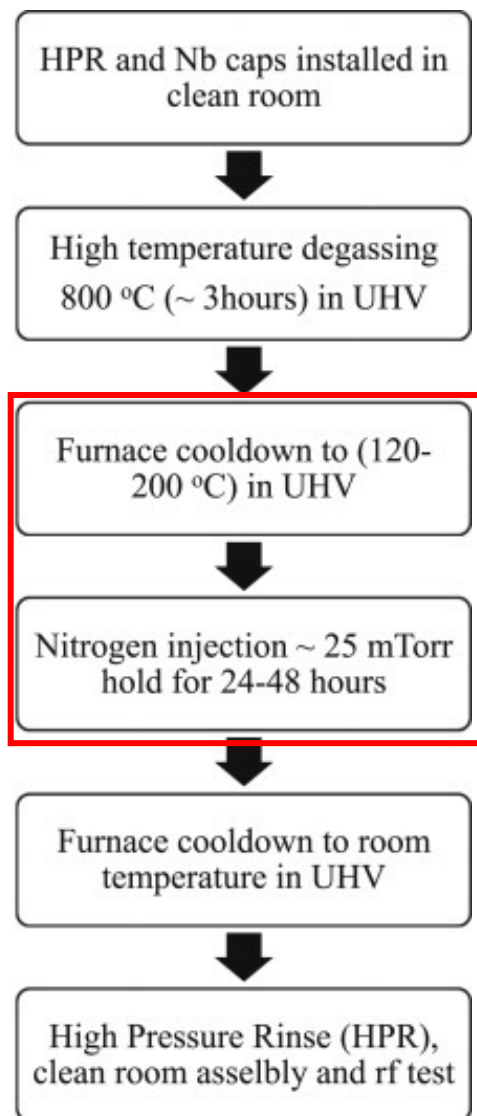

The 650 MHz cavity did not show anti-Q-slope
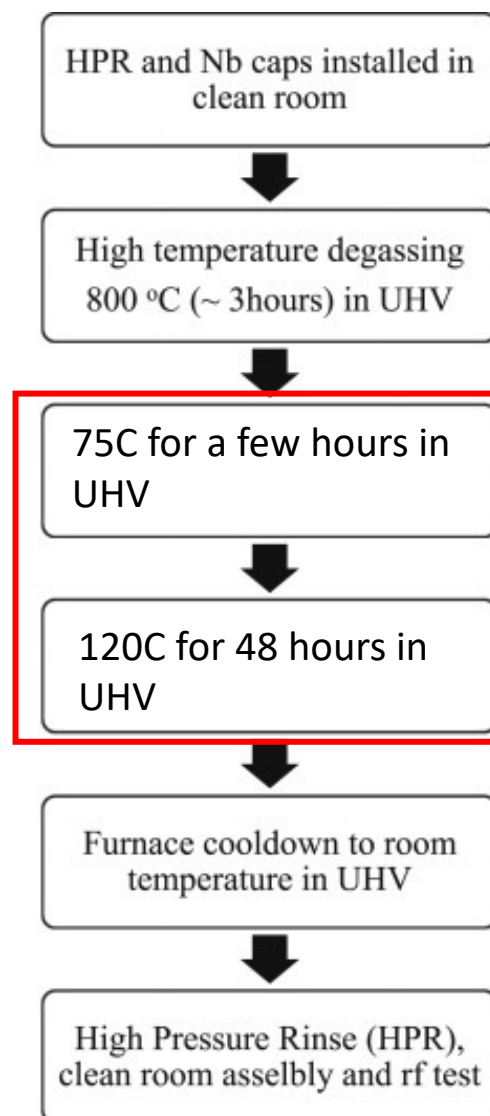
M. Martinello TTC2018

Legend:
- 650 MHz
- 650 MHz
- 1.3 GHz
- 2.6 GHz
- 3.9 GHz
- 3.9GHz_900C doping

R_T/R_T^0 vs E_{acc} (MV/m)

List of the different recipes

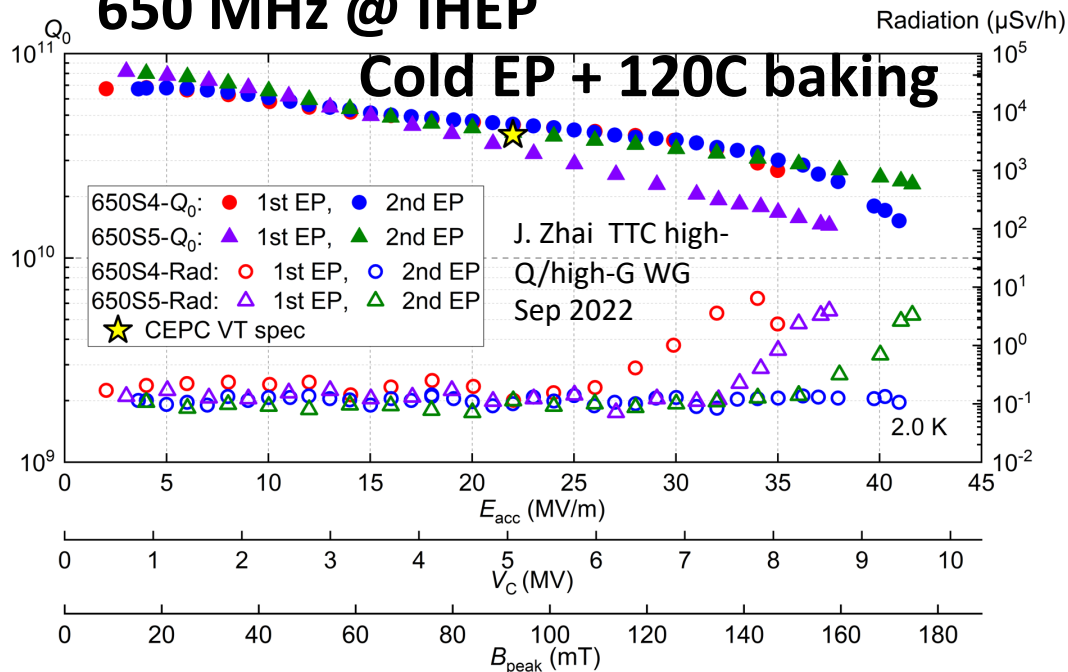| xNy doping	N-infusion	2-step baking (1.3 GHz)	Mid-T baking
High temperature degassing 800 °C (~ 3hours) in UHV	HPR and Nb caps installed in clean room	HPR and Nb caps installed in clean room	HPR and Nb caps installed in clean room
Nitrogen injection at the end of process (~ 25 mTorr) hold for 'x' mins	High temperature degassing 800 °C (~ 3hours) in UHV	High temperature degassing 800 °C (~ 3hours) in UHV	High temperature degassing 800 °C (~ 3hours) in UHV
Evacuate furnace and temperature hold for 'y' mins	Furnace cooldown to (120-200 °C) in UHV	75C for a few hours in UHV	Exposed to air for oxidation on purpose
Furnace cooldown to room temperature in UHV	Nitrogen injection ~ 25 mTorr hold for 24-48 hours	120C for 48 hours in UHV	250-400 C for a few hours in UHV
Electropolishing (5-10 µm)	Furnace cooldown to room temperature in UHV	Furnace cooldown to room temperature in UHV	Furnace cooldown to room temperature in UHV
High Pressure Rinse (HPR), clean room assembly and rf test	High Pressure Rinse (HPR), clean room assembly and rf test	High Pressure Rinse (HPR), clean room assembly and rf test	High Pressure Rinse (HPR), clean room assembly and rf test

P. Dhakal "Nitrogen doping and infusion in SRF cavities: A review" Phys Open 5 100034 2020

P. Sha et al. *Appl. Sci.* **12**, 546 (2022)

1-cell 704 MHz / 650 MHz with different recipes

650 MHz @ IHEP

P. Sha et al. *Appl. Sci.* **12**, 546 (2022)

- ■ EP baseline
- ● Mid-T furnace baking
- □ Rad: EP baseline
- ○ Rad: Mid-T furnace baking
- ★ CEPC VT spec

300C baking

At 2.0 K

650 MHz @ IHEP

Cold EP + 120C baking

650S4-Q₀: ● 1st EP, ● 2nd EP
650S5-Q₀: ▲ 1st EP, ▲ 2nd EP
650S4-Rad: ○ 1st EP, ○ 2nd EP
650S5-Rad: △ 1st EP, △ 2nd EP
★ CEPC VT spec

J. Zhai TTC high-Q/high-G WG Sep 2022

2.0 K

704 MHz @ CEA-Saclay

Vertical EP + 120C baking

- ■ VEP (200μm), No HT 2K
- ◆ +HT 650°Cx10h + VEP 2K
- ▲ 1.4K
- ✳ + baking 120°Cx48h   2K
- ✕ 1.4K
- ● + HF rinse 2K

Quench   Power

F. Eozenou et al TTC high-Q/high-G WG Sep 2022 LINAC22 THPOGE23

- **So far...120C for high-G, 300C for high-Q**
- The technique seems not matured enough in 650/704 MHz cavities compared to 1.3 GHz
- → Research opportunity for FCC 800 MHz that aims at highest field and Q in this frequency range

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Principle of SRF surface resistance and Q *at low field*

$$R_s \propto P \propto \hbar\omega \int_{\Delta}^{\infty} dE \, [f(E) - f(E + \hbar\omega)] \times N(E)N(E + \hbar\omega)$$

$f(E)$: distribution function $N(E)$: density of states

$$1/Q_0 \propto R_s \sim R_{\mathrm{BCS}}(T) + R_{\mathrm{res}}$$

Gap Δ

$T = 0$

$T > 0$

$T > 0$
$f(E) > 0$

$(E-\epsilon_F)/\Delta$

$E + \hbar\omega$ $\hbar\omega$

E

$E + \hbar\omega$

E $\hbar\omega$

All quasiparticles
$\Delta < E < \infty$

N(E)/N$_n$

Magnetic(?)
impurity (Dynes)

BCS
density
of state

$(E - E_F)/\Delta$

Generate

R$_s$ [nΩ]

R_{res}

Pure BCS $R_{res} = 0$

$R_{res} = 10$ nΩ

$R_{res} = 1$ nΩ

T$_c$/T
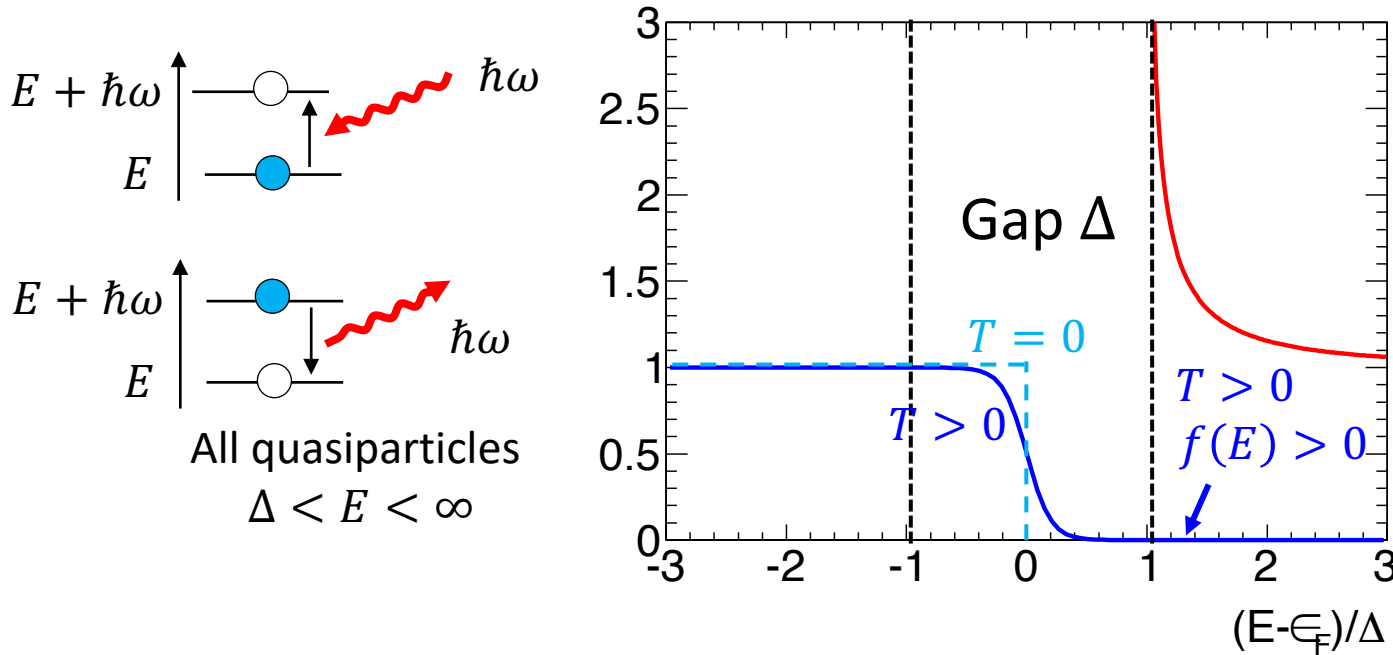
The overlap between $f(E)$ and $N(E)$ causes the resistance

- The pole of N(E) at Δ cause R_{BCS}
- The state below Δ causes R_{res}

→ Smearing of $N(E)$ decreases R_{BCS} and increases R_{res}
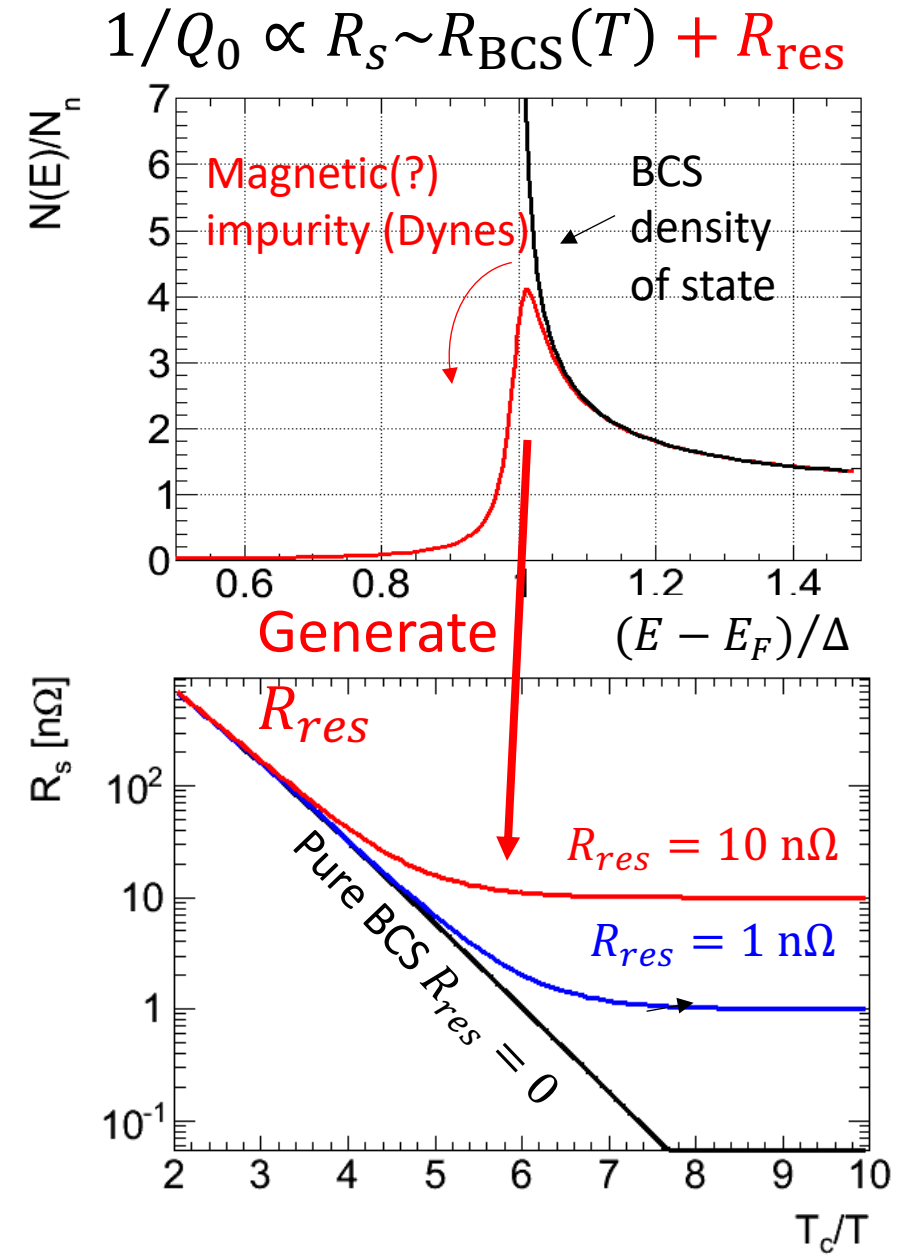
Optimize Q (*low field*) by two material parameters

Combination of pair-breaking scattering (Γ, Dynes parameter) and quasiparticle scattering ($\gamma = v_F/l$) can give a minimum of $R_{BCS} + R_{res}$ → maximum Q (mid-T bake?)
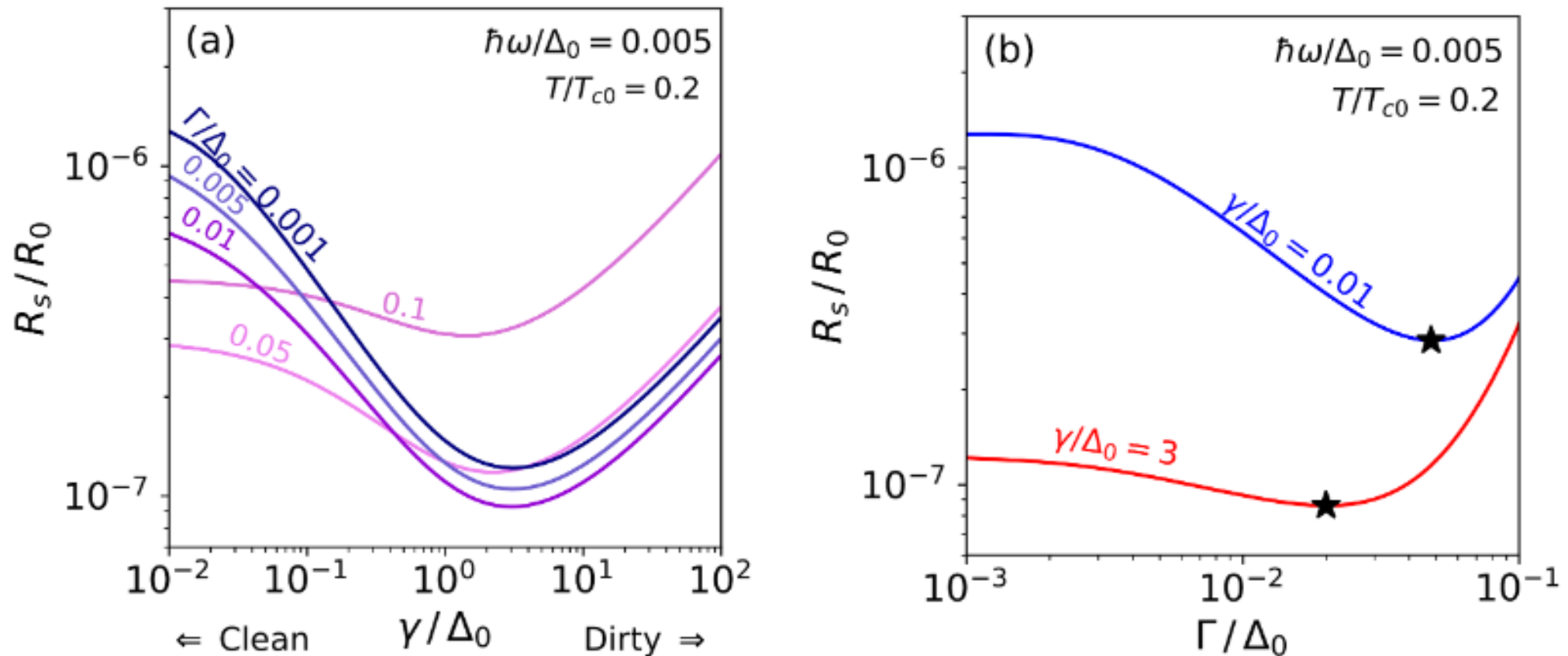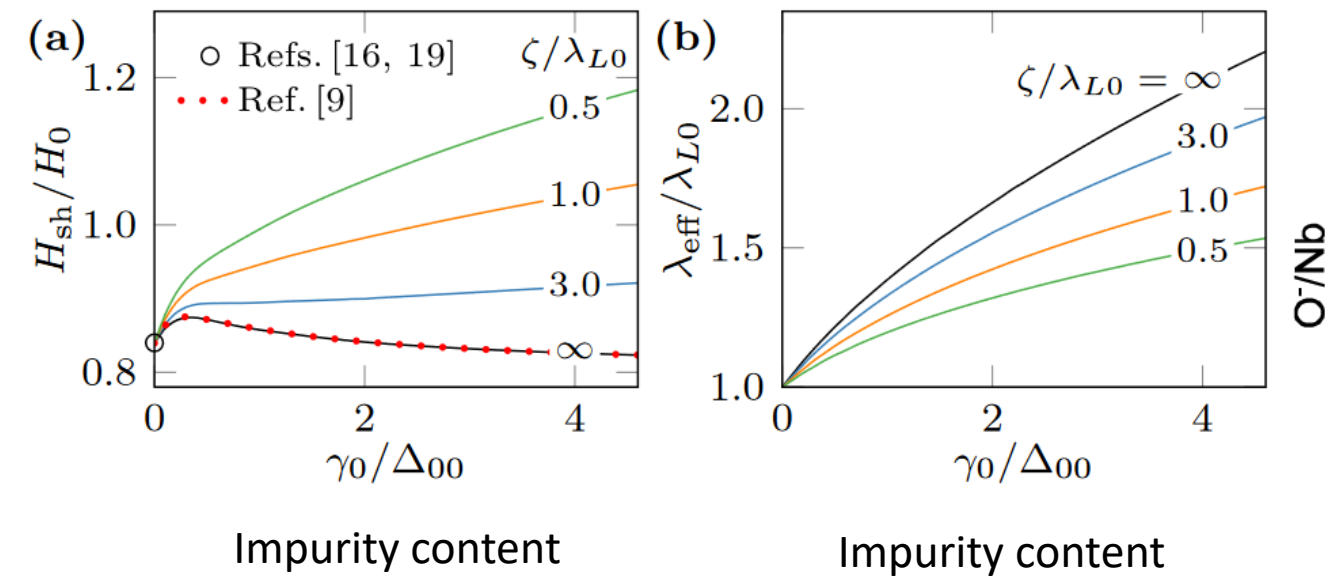
γ is conventional impurity scattering (mean free path) but Γ is not fully understood (magnetic impurity? Oxygen?)
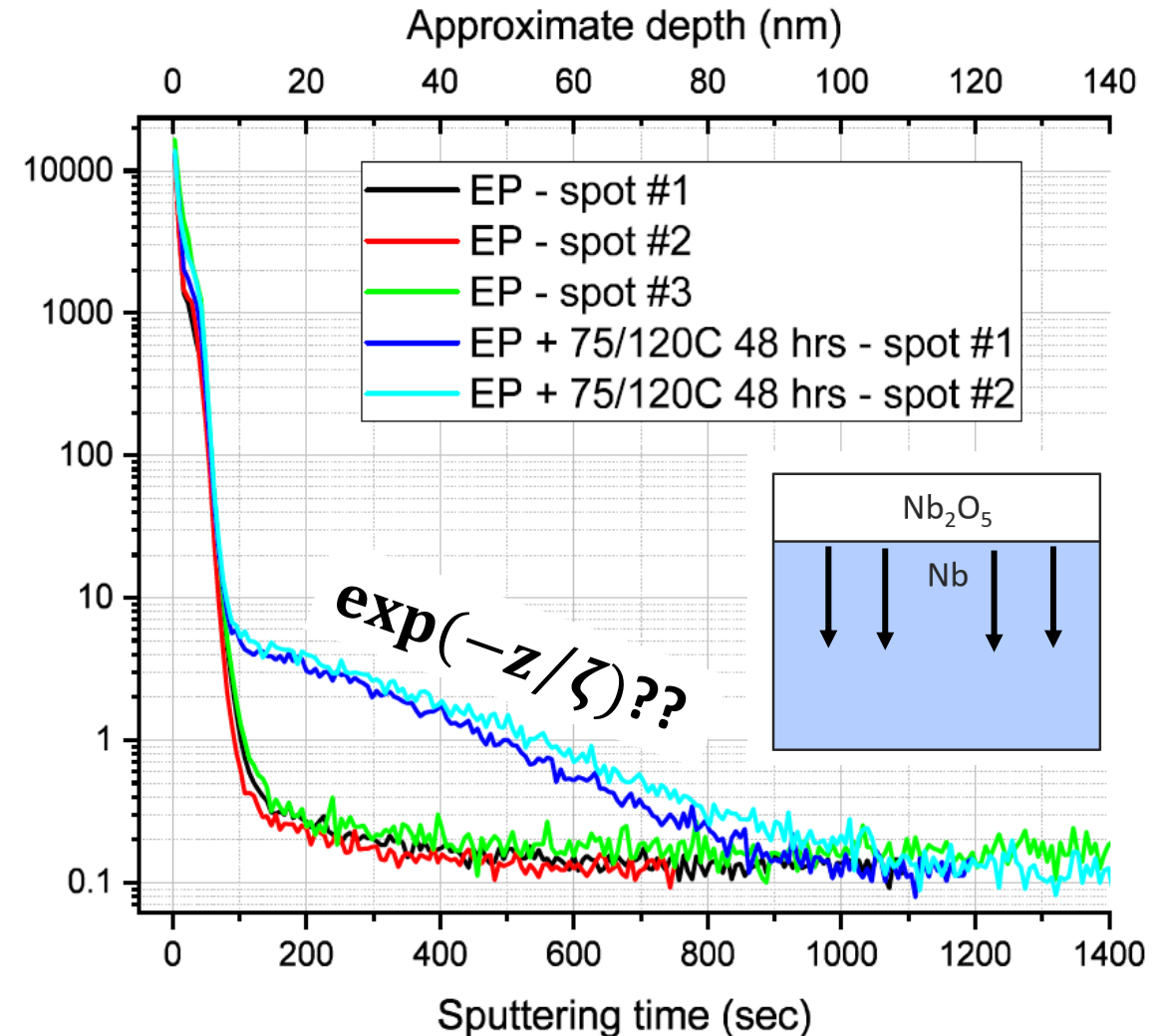
Higher/lower gradient by low-T baking

Inhomogeneous dislocations impacts H_{sh}
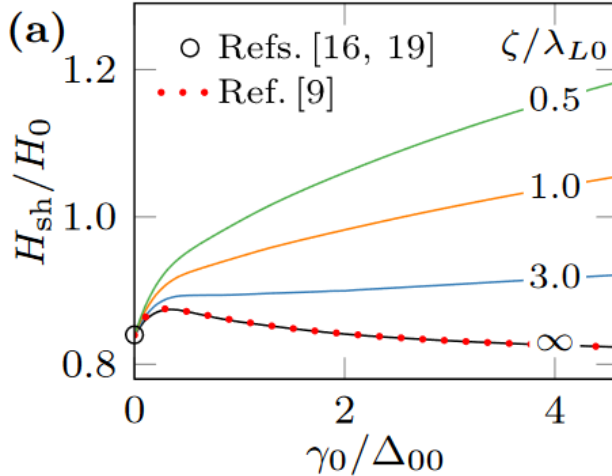
Parameter of inhomogeneity $\exp(-z/\zeta)$

Impurity content

Impurity content

→ Higher superheating fields can be achieved if surface impurity has inhomogeneous distribution

$\exp(-z/\zeta)??$

D. Bafia LCWS2023

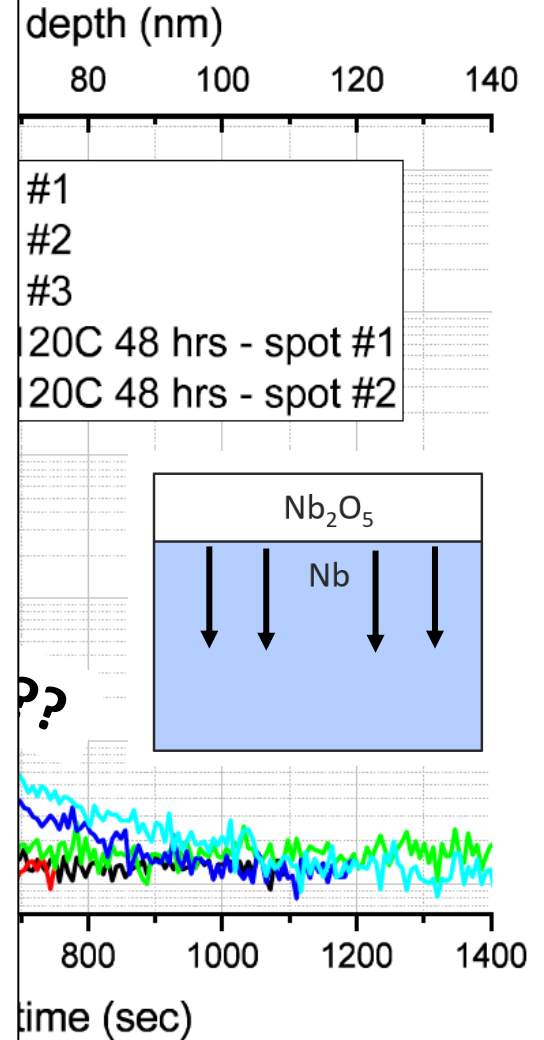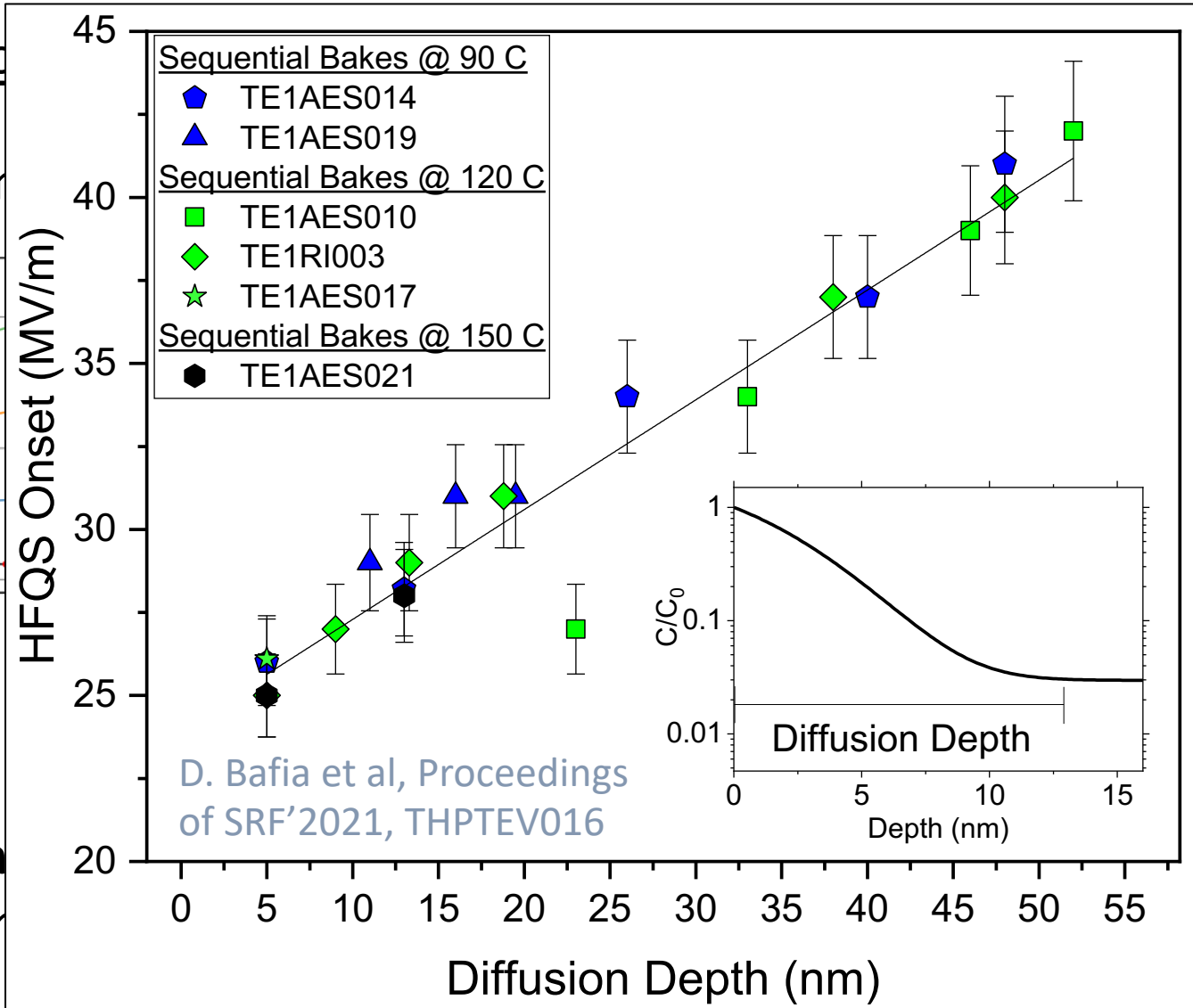Vudtiwat Ngampruetikorn and J. A. Sauls Phys. Rev. Research 1, 012015(R) 2019

Higher/lower gradient by low-T baking

Inhomogeneous dislo

Parameter of inho

Impurity content

→ Higher superheatin
surface impurity has i

Legend (on plot):
Sequential Bakes @ 90 C
- TE1AES014
- TE1AES019

Sequential Bakes @ 120 C
- TE1AES010
- TE1RI003
- TE1AES017

Sequential Bakes @ 150 C
- TE1AES021

D. Bafia et al, Proceedings of SRF'2021, THPTEV016

depth (nm)

#1
#2
#3
120C 48 hrs - spot #1
120C 48 hrs - spot #2

Nb₂O₅
Nb

??

D. Bafia LCWS2023

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Vudtiwat Ngampruetikorn and J. A. Sauls Phys. Rev. Research 1, 012015(R) 2019

Technical synergy to PERLE at Orsay

Standard CM based on
ESS design (4 cavities)

800 MHz 5 cells

Target Parameter	Unit	Value
Injection energy	MeV	7
Electron beam energy	MeV	500
Normalised Emittance $\gamma\varepsilon_{x,y}$	mm mrad	6
Average beam current	mA	20
Bunch charge	pC	500
Bunch length	mm	3
Bunch spacing	ns	25
RF frequency	MHz	801.58
Nominal gradient	MV/m	20.4
Target quality factor		10^{10}
Duty factor		CW

- **FCC and PERLE share the similar R&D goals in 800 MHz cavity performances**
- iSAS proposal (European funding: HORIZON-INFRA-2023-TECH-01)
  - Standardize CM for 700-800 MHz cavities (PERLE, FCC, ESS upgrade, SPL for MuCol, etc)
  - Industrialisation of this standard CM and its components, **but R&D is the first step**

Technical synergy to PERLE at Orsay

Standard CM based on
ESS design (4 cavities)
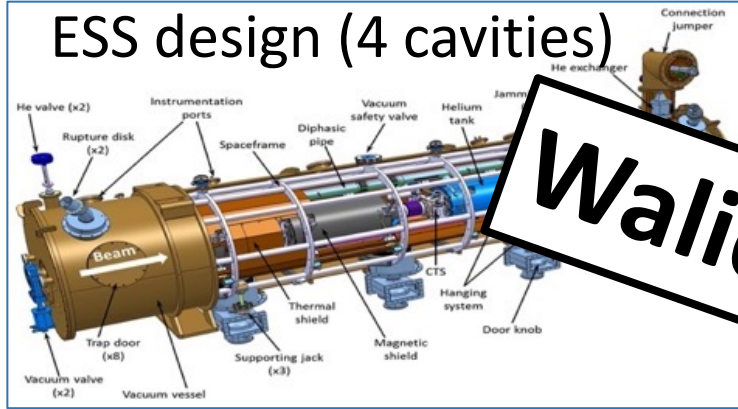
Walid Kaabi's talk on Thursday

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Conclusion

- FCC 800 MHz option demands highest field and Q out of non-1.3 GHz cavities
  - EP is mandatory and excellent baking/doping must be applied as well
  - The performance has been achieved in R&D and prototyping with 120C baking
  - Production yield in series cavities may be a challenge → industrialization of surface treatment
- N-doping has been successfully industrialized for LCLS-II and LCLS-II-HE
  - Systematic studies have focused on 1.3 GHz cavities
- Various baking and doping recipes have been tried for 650 / 704 MHz cavities
  - Encouraging results have been obtained
  - So far the standard 120C baking for 650/704 MHz 1-cell cavity showed the highest gradient
  - 300C baking showed the highest Q
  - More systematic studies need to be performed
- Microscopic theoretical understandings and doping/baking recipes show a gap
  - The most fundamental theory and phenomenological models have been proposed
  - Experimental evidences have been reported but it seems not sufficient to identify the root cause of the improvement by baking
- 800 MHz technology may define a standard CM in various future projects
  - FCC at CERN, PERLE at Orsay, proton drivers (ESS upgrade, SPL for MuCol, etc)
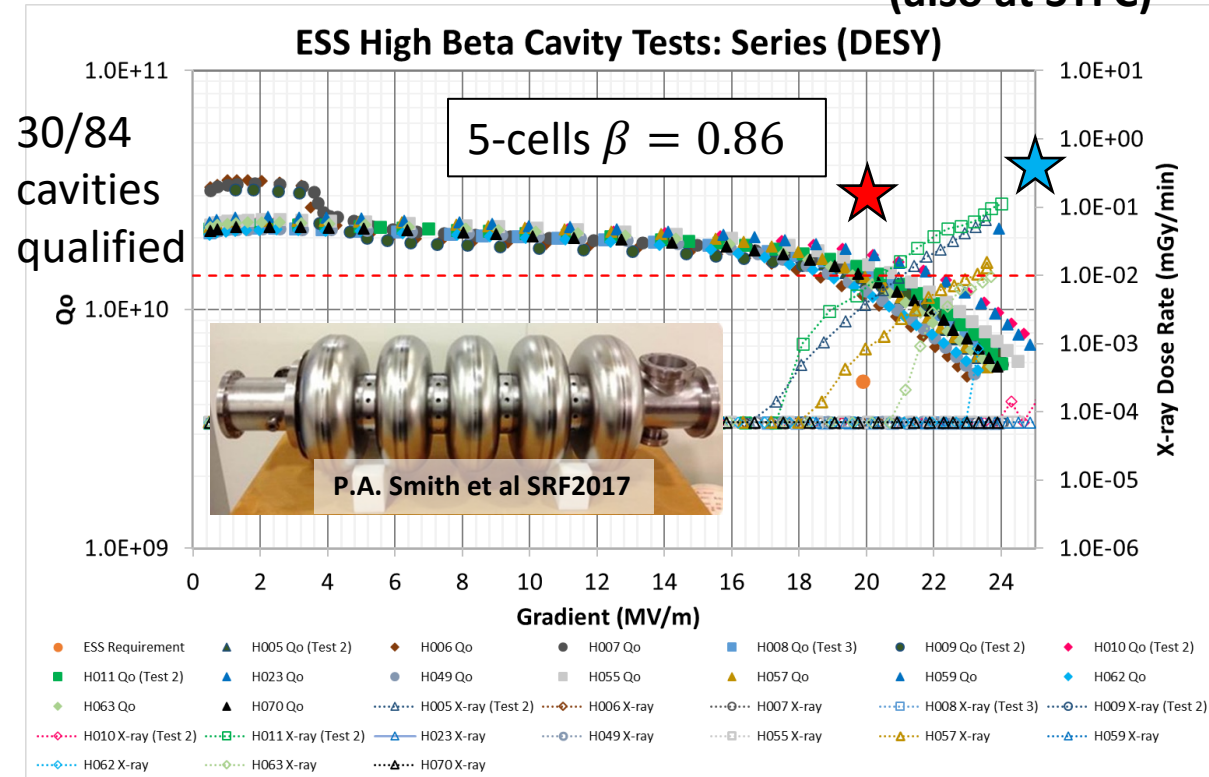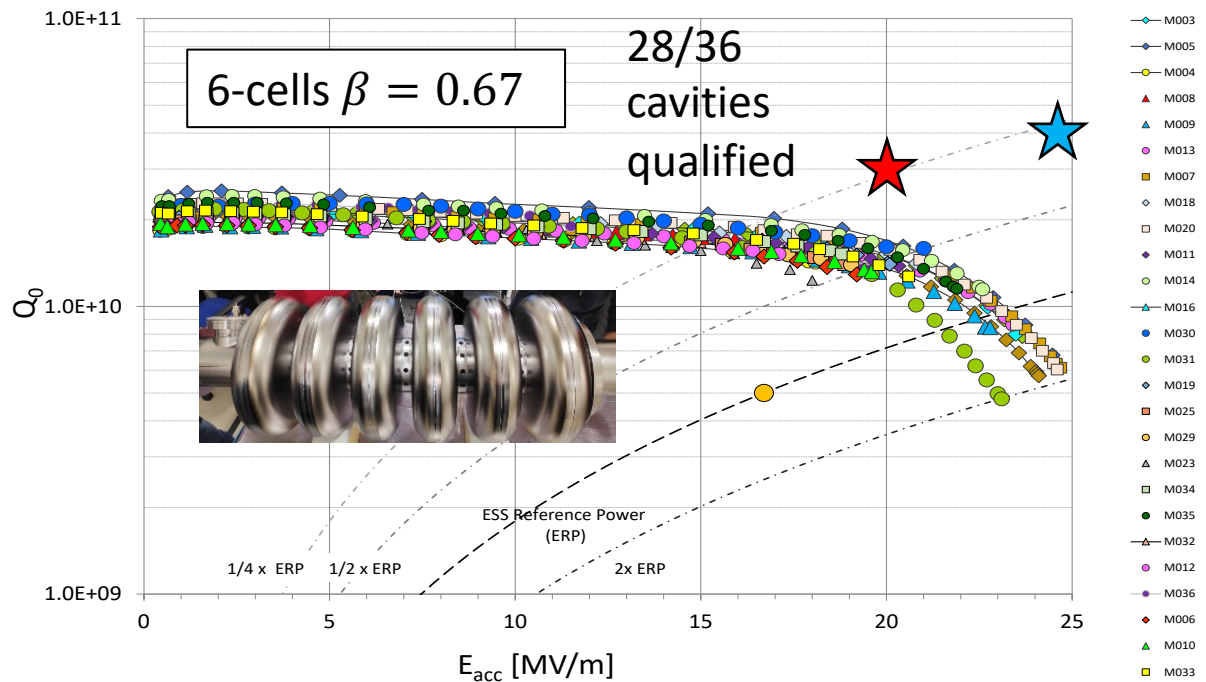 - IJCLab is initiating this research direction by the iSAS project proposal for EU funding

backup

Mass production: 5-/6-cell 704 MHz for ESS (March 2022)

(also at STFC)

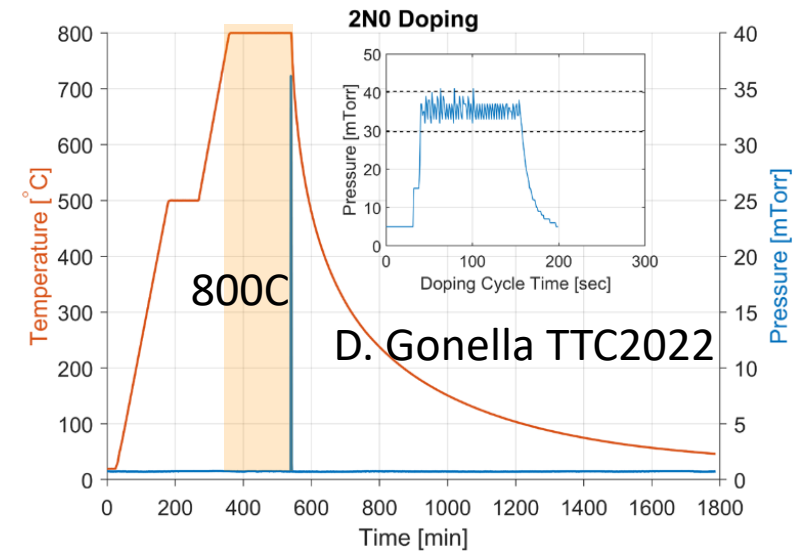**DESY and INFN-LASA**

Q_0 vs E_{acc} @ T=2K

6-cells $\beta = 0.67$

28/36 cavities qualified

ESS High Beta Cavity Tests: Series (DESY)

30/84 cavities qualified

5-cells $\beta = 0.86$

P.A. Smith et al SRF2017

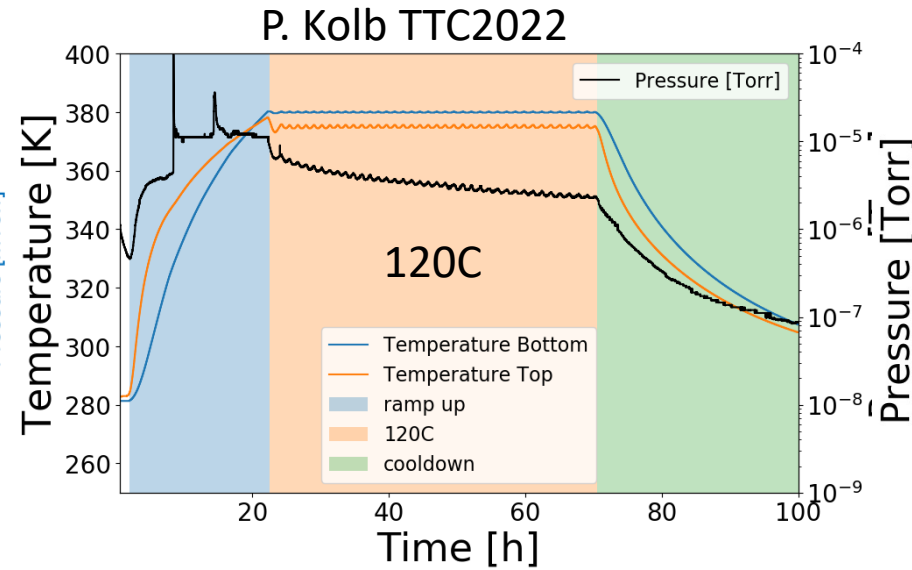| Step	Amount
Bulk BCP	90+110 um
600C annealing	10 hours
Final BCP	20 um

- $Q_0 > 10^{10}$ at $E_{acc} = 20$ MV/m has been statistically achieved
- No EP in the standard recipe
  - A couple of mid-β cavities were disqualified with steep Q-slope without field emission and (to be) treated by EP
- No low-T baking ← No need for very high gradient > 25 MV/m

M. Ellis "HB elliptical cavity manufacturing and testing" aTAC2022 ESS
D. Sertore "Progress with the recovery of missing MB cavities" aTAC2022 ESS

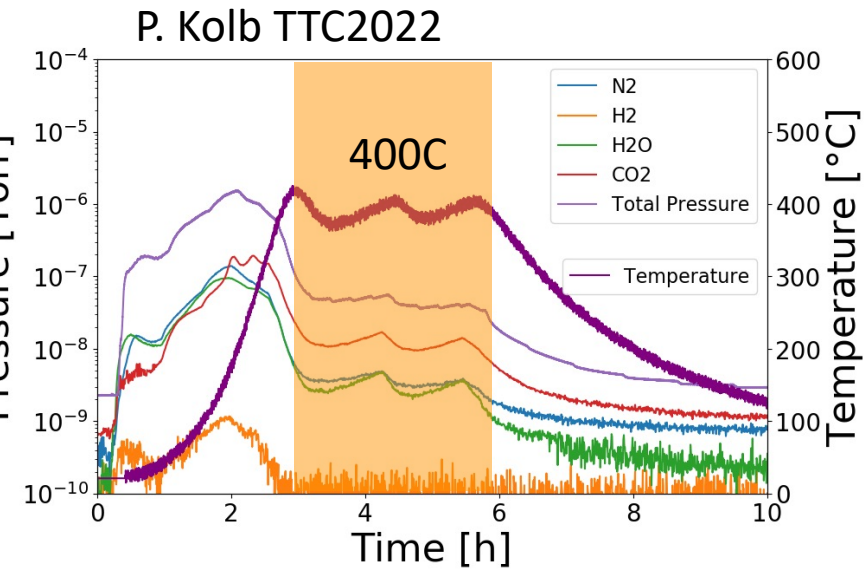# Temperature vs time

N-doping

Low-T baking

mid-T baking

Systematic studies to select xNy and temperature

Cavity	Heat Treatment Temperature [°C]	Doping Recipe	EP Post Doping [μm]	Prepared at	Quench [MV/m]	Q_0 at 16 MV/m (21 MV/m)
CAV357	925	2/6	7	EZ/RI	17.2	3×10^{10}
CAV358[1]	925	2/6	7	EZ/RI	20.8	2.7×10^{10}
CAV360[1]	925	2/6	7	EZ/RI	20.2	3×10^{10}
CAV361	925	2/6	7	EZ/RI	19.1	2.8×10^{10}
CAV349	975	2/0	7	EZ/RI	15	2.4×10^{10}
CAV350	975	2/0	7	EZ/RI	20.6	3.5×10^{10}
CAV363	925	2/0	7	EZ/RI	21.6	3.5×10^{10} (2.9)
CAV364	925	2/0	7	EZ/RI	22.5	2.4×10^{10}
CAV363	925	2/0	10	EZ/RI	24.5	3×10^{10} (2.9)
CAV350	975	2/0	10	EZ/RI	22.8	3×10^{10} (2.9)
CAV355	925	3/60	11	EZ/RI	18.1	3.1×10^{10}
CAV356	925	3/60	11	EZ/RI		
CAV359	925	3/60	11	EZ/RI	17.2	3.8×10^{10}
CAV362	925	3/60	11	EZ/RI	18.3	3.8×10^{10}
CAV351	975	3/60	11	EZ/RI		
CAV352	975	3/60	11	EZ/RI	15.5	2.3×10^{10}
CAV353	975	3/60	11	EZ/RI	16.9	3.1×10^{10}
CAV354	975	3/60	11	EZ/RI		
CAV353[1]	975	3/60	15	EZ/RI	17	3.5×10^{10}
CAV0017	900	2/0	7	FNAL	20	3×10^{10}
CAV0017	900	2/0	7	FNAL	25.5	3×10^{10}
CAV0018	900	2/0	7	FNAL	20	3×10^{10}
TB9RI022	800	2/0	7	FNAL	32	2.5×10^{10}