Instantaneous Q_l/Q_{ext}-Measurements in CEBAF incl. Transmission Line Calibration

PIT Meeting

2019-08-12

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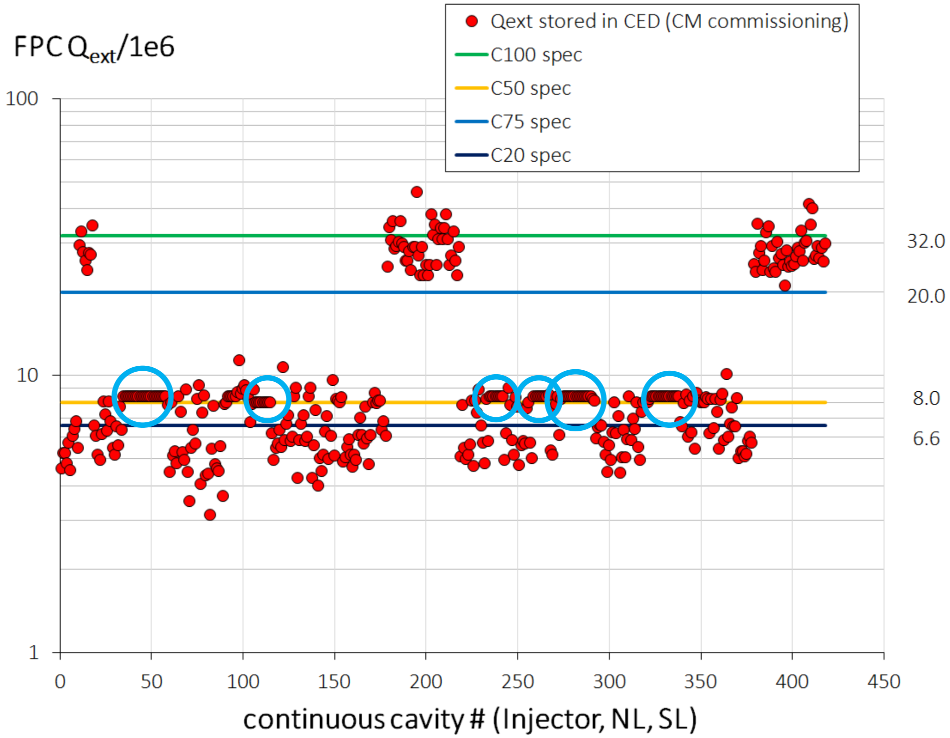
Acknowledgement: Thanks to Rongli Geng for “Brown bag” discussions on CEBAF issues

CEBAF Element Database

- The CED carries Q_{ext}-values for cavities as measured during cryomodule commissioning (partially dating back to 2010)
- Not clear whether or not the stub-tuning was done before or after commissioning so that actual Q_{ext}-values could have changed since commissioning
- We do not know the discrepancy between commissioning (CED) and actual measured Q_{ext}-values after stub tuning
- Q_{ext}-values measured during/after stub-tuning are not captured electronically
- Q_{ext}-values in the CED were ever updated to my knowledge
- Values for several C50 cryomodules are just specs, no measured data were recorded in CED

→ any data-mining of commissioning data is very tedious



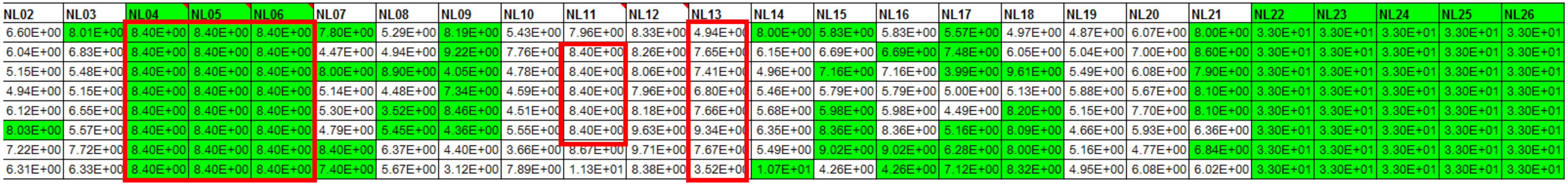
Stub Tuner Installation

O:\ees\RF\WAVEGUIDE\Stub Tuner Info

Thanks to R. Nelson and J. Benesch for providing link

Latest entry/info: 2016-01-04

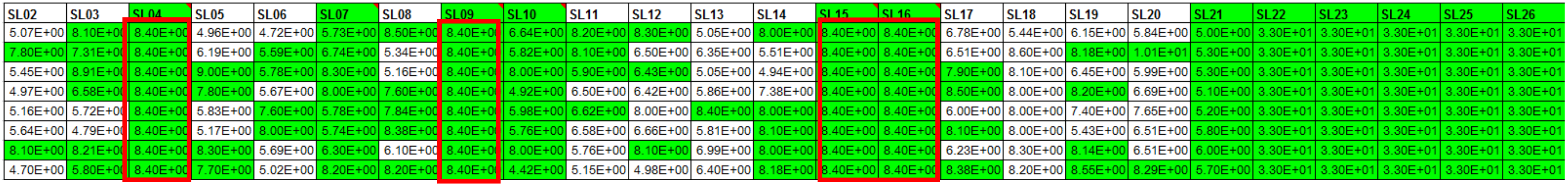
North Linac (NL): 107 (53.5%) out of 200 cavities have stub tuners



NL02	NL03	NL04	NL05	NL06	NL07	NL08	NL09	NL10	NL11	NL12	NL13	NL14	NL15	NL16	NL17	NL18	NL19	NL20	NL21	NL22	NL23	NL24	NL25	NL26
6.60E+00	8.01E+00	8.40E+00	8.40E+00	8.40E+00	7.80E+00	5.29E+00	8.19E+00	5.43E+00	7.96E+00	8.33E+00	4.94E+0	8.00E+00	5.83E+00	5.83E+00	5.57E+00	4.97E+00	4.87E+00	6.07E+00	8.00E+00	3.30E+01	3.30E+01	3.30E+01	3.30E+01	3.30E+01
6.04E+00	6.83E+00	8.40E+00	8.40E+00	8.40E+00	4.47E+00	4.94E+00	9.22E+00	7.76E+00	8.40E+00	8.26E+00	7.65E+0	6.15E+00	6.69E+00	6.69E+00	7.48E+00	6.05E+00	5.04E+00	7.00E+00	8.60E+00	3.30E+01	3.30E+01	3.30E+01	3.30E+01	3.30E+01
5.15E+00	5.48E+00	8.40E+00	8.40E+00	8.40E+00	8.00E+00	8.90E+00	4.05E+00	4.78E+00	8.40E+00	8.06E+00	7.41E+0	4.96E+00	7.16E+00	7.16E+00	3.99E+00	9.61E+00	5.49E+00	6.08E+00	7.90E+00	3.30E+01	3.30E+01	3.30E+01	3.30E+01	3.30E+01
4.94E+00	5.15E+00	8.40E+00	8.40E+00	8.40E+00	5.14E+00	4.48E+00	7.34E+00	4.59E+00	8.40E+00	7.96E+00	6.80E+0	5.46E+00	5.79E+00	5.79E+00	5.00E+00	5.13E+00	5.88E+00	5.67E+00	8.10E+00	3.30E+01	3.30E+01	3.30E+01	3.30E+01	3.30E+01
6.12E+00	6.55E+00	8.40E+00	8.40E+00	8.40E+00	5.30E+00	3.52E+00	8.46E+00	4.51E+00	8.40E+00	8.18E+00	7.66E+0	5.68E+00	5.98E+00	5.98E+00	4.49E+00	8.20E+00	5.15E+00	7.70E+00	8.10E+00	3.30E+01	3.30E+01	3.30E+01	3.30E+01	3.30E+01
8.03E+00	5.57E+00	8.40E+00	8.40E+00	8.40E+00	4.79E+00	5.45E+00	4.36E+00	5.55E+00	8.40E+00	9.63E+00	9.34E+0	6.35E+00	8.36E+00	8.36E+00	5.16E+00	8.09E+00	4.66E+00	5.93E+00	6.36E+00	3.30E+01	3.30E+01	3.30E+01	3.30E+01	3.30E+01
7.22E+00	7.72E+00	8.40E+00	8.40E+00	8.40E+00	8.40E+00	6.37E+00	4.40E+00	3.66E+00	8.67E+00	9.71E+00	7.67E+0	5.49E+00	9.02E+00	9.02E+00	6.28E+00	8.00E+00	5.16E+00	4.77E+00	6.84E+00	3.30E+01	3.30E+01	3.30E+01	3.30E+01	3.30E+01
6.31E+00	6.33E+00	8.40E+00	8.40E+00	8.40E+00	7.40E+00	5.67E+00	3.12E+00	7.89E+00	1.13E+01	8.38E+00	3.52E+0	1.07E+01	4.26E+00	4.26E+00	7.12E+00	8.32E+00	4.95E+00	6.08E+00	6.02E+00	3.30E+01	3.30E+01	3.30E+01	3.30E+01	3.30E+01

now C50/C75 CM
(not updated)

South Linac (SL): 140 (70%) out of 200 cavities have stub tuners



SL02	SL03	SL04	SL05	SL06	SL07	SL08	SL09	SL10	SL11	SL12	SL13	SL14	SL15	SL16	SL17	SL18	SL19	SL20	SL21	SL22	SL23	SL24	SL25	SL26
5.07E+00	8.10E+00	8.40E+00	4.96E+00	4.72E+00	5.73E+00	8.50E+00	8.40E+0	6.64E+00	8.20E+00	8.30E+00	5.05E+00	8.00E+00	8.40E+00	8.40E+00	6.78E+00	5.44E+00	6.15E+00	5.84E+00	5.00E+00	3.30E+01	3.30E+01	3.30E+01	3.30E+01	3.30E+01
7.80E+00	7.31E+00	8.40E+00	6.19E+00	5.59E+00	6.74E+00	5.34E+00	8.40E+0	5.82E+00	8.10E+00	6.50E+00	6.35E+00	5.51E+00	8.40E+00	8.40E+00	6.51E+00	8.60E+00	8.18E+00	1.01E+01	5.30E+00	3.30E+01	3.30E+01	3.30E+01	3.30E+01	3.30E+01
5.45E+00	8.91E+00	8.40E+00	9.00E+00	5.78E+00	8.30E+00	5.16E+00	8.40E+0	8.00E+00	5.90E+00	6.43E+00	5.05E+00	4.94E+00	8.40E+00	8.40E+00	7.90E+00	8.10E+00	6.45E+00	5.99E+00	5.30E+00	3.30E+01	3.30E+01	3.30E+01	3.30E+01	3.30E+01
4.97E+00	6.58E+00	8.40E+00	7.80E+00	5.67E+00	8.00E+00	7.60E+00	8.40E+0	4.92E+00	6.50E+00	6.42E+00	5.86E+00	7.38E+00	8.40E+00	8.40E+00	8.50E+00	8.00E+00	8.20E+00	6.69E+00	5.10E+00	3.30E+01	3.30E+01	3.30E+01	3.30E+01	3.30E+01
5.16E+00	5.72E+00	8.40E+00	5.83E+00	7.60E+00	5.78E+00	7.84E+00	8.40E+0	5.98E+00	6.62E+00	8.00E+00	8.40E+00	8.00E+00	8.40E+00	8.40E+00	6.00E+00	8.00E+00	7.40E+00	7.65E+00	5.20E+00	3.30E+01	3.30E+01	3.30E+01	3.30E+01	3.30E+01
5.64E+00	4.79E+00	8.40E+00	5.17E+00	8.00E+00	5.74E+00	8.38E+00	8.40E+0	5.76E+00	6.58E+00	6.66E+00	5.81E+00	8.10E+00	8.40E+00	8.40E+00	8.10E+00	8.00E+00	5.43E+00	6.51E+00	5.80E+00	3.30E+01	3.30E+01	3.30E+01	3.30E+01	3.30E+01
8.10E+00	8.21E+00	8.40E+00	8.30E+00	5.69E+00	6.30E+00	6.10E+00	8.40E+0	8.00E+00	5.76E+00	8.10E+00	6.99E+00	8.00E+00	8.40E+00	8.40E+00	6.23E+00	8.30E+00	8.14E+00	6.51E+00	6.00E+00	3.30E+01	3.30E+01	3.30E+01	3.30E+01	3.30E+01
4.70E+00	5.80E+00	8.40E+00	7.70E+00	5.02E+00	8.20E+00	8.20E+00	8.40E+0	4.42E+00	5.15E+00	4.98E+00	6.40E+00	8.18E+00	8.40E+00	8.40E+00	8.38E+00	8.20E+00	8.55E+00	8.29E+00	5.70E+00	3.30E+01	3.30E+01	3.30E+01	3.30E+01	3.30E+01

CEBAF Element Database

- C20 cavities possess the lowest Q_{ext}-values, which are never matched at any beam current level and reasonably achievable E_{acc}-values
- Reducing the vulnerability to microphonics might be a reason to favor too low Q_{ext}-values (unmatched conditions), but there are counter-arguments
- Operational consequences can be manifold:
- Larger reflections → strong standing waves in transmission lines

→ more frequent waveguide arcing and cavity tripping…

→ enhanced RF losses in waveguide components such as the cold RF windows that deposit heat in He bath → reduce 'combined Q_0'

→ Combined Q_0: We cannot differentiate between SRF wall losses and other 2 K losses in standard Q_0-measurements; the other contributions can yet be significant, e.g. we verified a 50% Q_0-reduction last year for a C50 cavity (1L13) due to different standing wave pattern in transmission line, while SRF wall losses were kept constant

→ Unnecessary power consumption

Forward & Reflected Power

- Recall general relationships of forward and reflected power (on crest):

$$P_f = \frac{{V_c}^2}{{}^{R}\!/_{Q} \cdot Q_l} \cdot \frac{1+\beta}{4\beta} \cdot \left\{\left[1 + \frac{I_{tot}\, {}^{R}\!/_{Q}\, Q_l}{V_c}\right]^2 + tan^2\Psi\right\}$$

$$P_r = \frac{{V_c}^2}{\underbrace{{}^{R}\!/_{Q} \cdot Q_l}_{R_l}} \cdot \frac{1+\beta}{4\beta} \cdot \left\{\left[\frac{\beta-1}{\beta+1} - \frac{I_{tot}\, {}^{R}\!/_{Q}\, Q_l}{V_c}\right]^2 + tan^2\Psi\right\}$$

$$\tan(\Psi) = Q_l \cdot \left(\frac{\omega_0}{\omega} - \frac{\omega}{\omega_0}\right)$$

$$\frac{1}{Q_l} = \frac{1}{Q_{ext}} + \frac{1}{Q_0}$$

$$Q_l \approx Q_{ext}$$

$$with\ \beta = \frac{Q_0}{Q_{ext}}$$

$$\rightarrow \frac{Q_0}{Q_l} = \beta + 1$$

$$R_l = \frac{{}^{R}\!/_{Q} \cdot Q_0}{\beta+1} = \frac{R}{\beta+1}$$

$$\underbrace{P_f - P_r}_{P_{cav}} = \frac{{V_c}^2}{{}^{R}\!/_{Q} \cdot Q_0} + I_{tot} \cdot V_c$$

beam loading

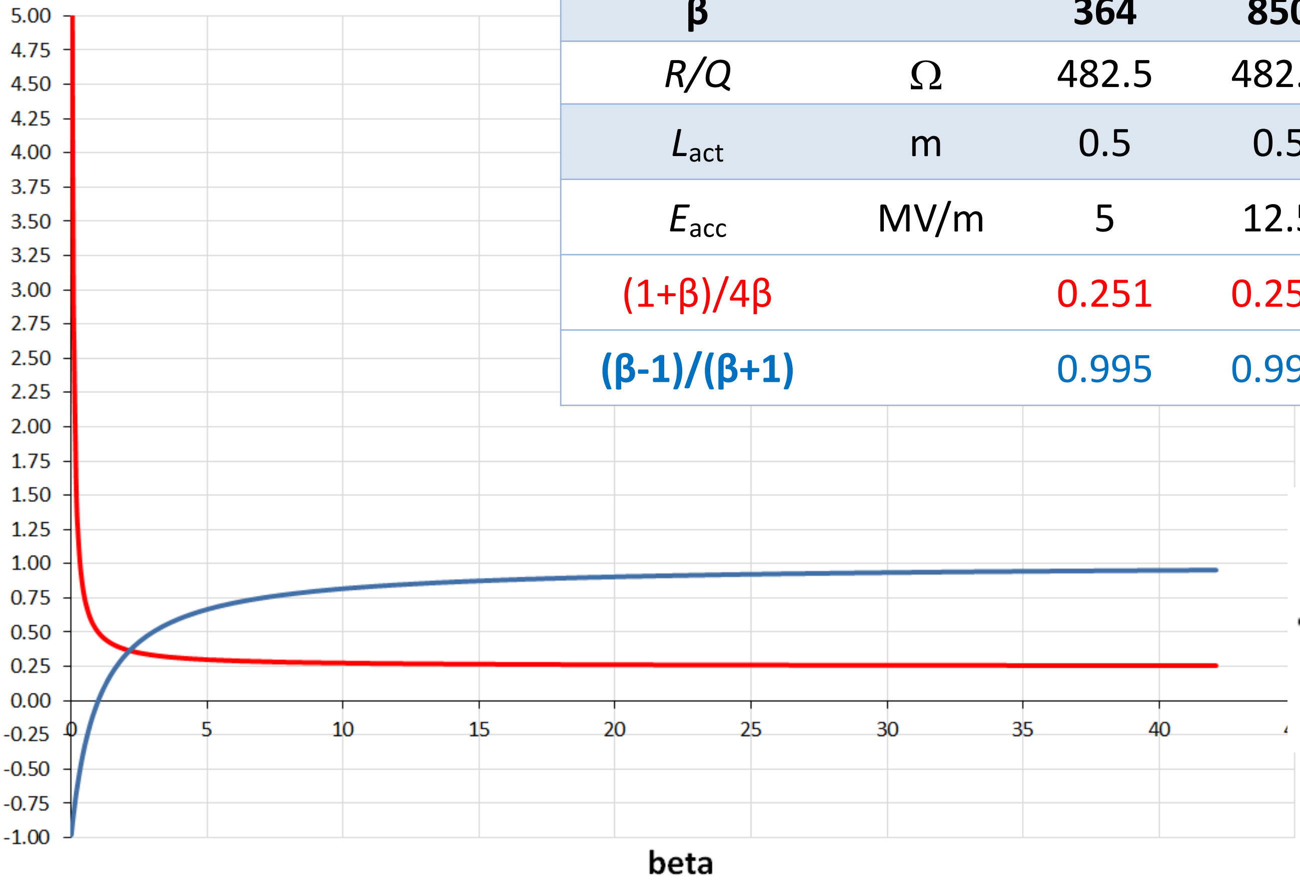
for optimum match: $\dfrac{\beta-1}{\beta+1} - \dfrac{I_{tot}R}{(\beta+1)\,V_c} = 0$

$$\boxed{\rightarrow \beta_{opt} = 1 + \frac{I_{tot}R}{V_c}}$$

CEBAF Cavity Specs and Coupling Beta

$$\frac{1+\beta}{4\beta} \quad \text{and} \quad \frac{\beta-1}{\beta+1}$$

Parameter	Units	C20	C50	C75	C100
Q_0 at 2.07 K		2.4e9	6.8e9	8.0e9	7.2e9
Q_{ext} spec		6.6e6	8.0e6	2.0e7	3.2e7
β		**364**	**850**	**400**	**225**
R/Q	Ω	482.5	482.5	525.4	868.9
L_{act}	m	0.5	0.5	0.4916	0.7
E_{acc}	MV/m	5	12.5	19.1	19.2
(1+β)/4β		0.251	0.250	0.251	0.251
(β-1)/(β+1)		0.995	0.998	0.994	0.991



for β >> 1:

$$\begin{cases} \frac{\beta-1}{\beta+1} \approx 1 \\ \frac{1+\beta}{4\beta} \approx \frac{1}{4} \end{cases}$$

Forward Power & Reflected Power

- Good approximations with non-significant penalty for CEBAF:

$$P_f \approx \frac{{V_c}^2}{R/_{Q} \cdot Q_l} \cdot \frac{1}{4} \cdot \left\{ \left[1 + \frac{I_{tot}\, R/_{Q}\, Q_l}{V_c} \right]^2 + tan^2\Psi \right\}$$

$$P_r \approx \frac{{V_c}^2}{R/_{Q} \cdot Q_l} \cdot \frac{1}{4} \left\{ \left[1 - \frac{I_{tot}\, R/_{Q}\, Q_l}{V_c} \right]^2 + tan^2\Psi \right\}$$

- Each equation can be solved for Q_l

Solve for Q_l using P_{fwd} (no approximation yet)

$$Q_l = \frac{{V_c}^2}{R/_Q \cdot P_f} \cdot \frac{1+\beta}{4\beta} \cdot \left\{ \left[1 + \frac{R/_Q\, I_{tot} Q_l}{V_c} \right]^2 + tan^2\Psi \right\}$$

$$Q_l = 2A \cdot D(\beta) \cdot \{[1 + B \cdot Q_l]^2 + C\}$$

$${Q_l}^2 + Q_l \cdot \frac{(2ABD(\beta) - 1)}{AB^2D(\beta)} + \frac{(1 + C)}{B^2} = 0$$

$$A = \frac{{V_c}^2}{R/_Q \cdot P_f} \qquad C = tan^2\Psi$$

$$B = \frac{I_{tot}\, R/_Q}{V_c} \qquad D(\beta) = \frac{1+\beta}{4\beta}$$

$$Q_l = -\frac{(2ABD(\beta) - 1) \pm \sqrt{1 - 4ABD(\beta) - (2ABD(\beta))^2 C}}{2AB^2D(\beta)}$$

$$AB = \frac{{V_c}^2}{R/_Q \cdot P_f} \cdot \frac{I_{tot}\, R/_Q}{V_c} = \frac{I_{tot} V_c}{P_f} \qquad AB^2 = \frac{I_{tot} V_c}{P_f} \cdot \frac{I_{tot}\, R/_Q}{V_c} = \frac{R/_Q \cdot {I_{tot}}^2}{P_f}$$

$$Q_l = \frac{\dfrac{P_f}{2 \cdot \left(\dfrac{1+\beta}{4\beta}\right)} - I_{tot} V_c \mp \dfrac{P_f}{2 \cdot \left(\dfrac{1+\beta}{4\beta}\right)} \cdot \sqrt{1 - \dfrac{4 I_{tot} V_c}{P_f} \left(\dfrac{1+\beta}{4\beta}\right) - \dfrac{4{I_{tot}}^2 \cdot {V_c}^2}{{P_f}^2} \left(\dfrac{1+\beta}{4\beta}\right)^2 tan^2\Psi}}{R/_Q\, {I_{tot}}^2}$$

Solve for Q_l using P_{ref} (no approximation yet)

- We get a similar expression when utilizing the reflected power

$$P_r = \frac{V_c^2}{R_L}\frac{1+\beta}{4\beta}\left\{\left[\frac{\beta-1}{1+\beta} - \frac{I_{tot}R_L}{V_c}\right]^2 + \tan^2\Psi\right\}$$

$$Q_l = \frac{\frac{P_r}{2\cdot\left(\frac{1+\beta}{4\beta}\right)} + I_{tot}V_c\left(\frac{\beta-1}{\beta+1}\right) \pm \frac{P_r}{2\cdot\left(\frac{1+\beta}{4\beta}\right)}\sqrt{1+\frac{4I_{tot}V_c}{P_r}\left(\frac{1+\beta}{4\beta}\right)\left(\frac{\beta-1}{\beta+1}\right) - \frac{4{I_{tot}}^2\cdot{V_c}^2}{{P_r}^2}\left(\frac{1+\beta}{4\beta}\right)^2 tan^2\Psi}}{{}^{R}/_{Q}\,{I_{tot}}^2}$$

- Now let's approximate:

$$\frac{1+\beta}{4\beta} \approx \frac{1}{4} \qquad \frac{\beta-1}{\beta+1} \approx 1$$

Solve for Q_l using P_fwd and P_ref

$$Q_l(P_f, I_{tot}, V_c, \Psi, \frac{R}{Q}) = \frac{2P_f - I_{tot}V_c \mp 2P_f\sqrt{1 - \frac{I_{tot}V_c}{P_f} - \frac{{I_{tot}}^2 \cdot {V_c}^2}{4{P_f}^2}tan^2\Psi}}{{}^{R}/_{Q}\, {I_{tot}}^2}$$

$$Q_l(P_r, I_{tot}, V_c, \Psi, \frac{R}{Q}) = \frac{2P_r + I_{tot}V_c \pm 2P_r\sqrt{1 + \frac{I_{tot}V_c}{P_r} - \frac{{I_{tot}}^2 \cdot {V_c}^2}{4{P_r}^2}tan^2\Psi}}{{}^{R}/_{Q}\, {I_{tot}}^2}$$

- All dependent variables are measurable, cavity parameters are known
- **We theoretically have all information to record the loaded *Q* (~external *Q*) of any cavity in CEBAF at any instant of time**
- **Only negative signs are valid**

Solve for Q_l using P_{fwd} and P_{ref}

$$Q_l(P_f, I_{tot}, V_c, \Psi, \frac{R}{Q}) = \frac{2P_f - I_{tot}V_c - 2P_f\sqrt{1 - \frac{I_{tot}V_c}{P_f} - \frac{{I_{tot}}^2 \cdot {V_c}^2}{4{P_f}^2}tan^2\Psi}}{{}^R/_Q\, {I_{tot}}^2}$$

$$Q_l(P_r, I_{tot}, V_c, \Psi, \frac{R}{Q}) = \frac{2P_r + I_{tot}V_c - 2P_r\sqrt{1 + \frac{I_{tot}V_c}{P_r} - \frac{{I_{tot}}^2 \cdot {V_c}^2}{4{P_r}^2}tan^2\Psi}}{{}^R/_Q\, {I_{tot}}^2}$$

Cavity parameter

CRFP (kW)
CRRP (kW)
GMES (MV/m) → V_c = GMESL_{act}*
Detuning angle (T)DETA (deg.)
R/Q

Beam currents and recirculating passes

IBC1H04CRCUR2 (μA), MMSHLAPASS
IBC2C24CRCUR3 (nA), MMSHLBPASS
IBC3H00CRCUR4 (μA), MMSHLCPASS
IBCAD00CRCUR6 (nA), MMSHLDPASS

South linac with Hall D beam current

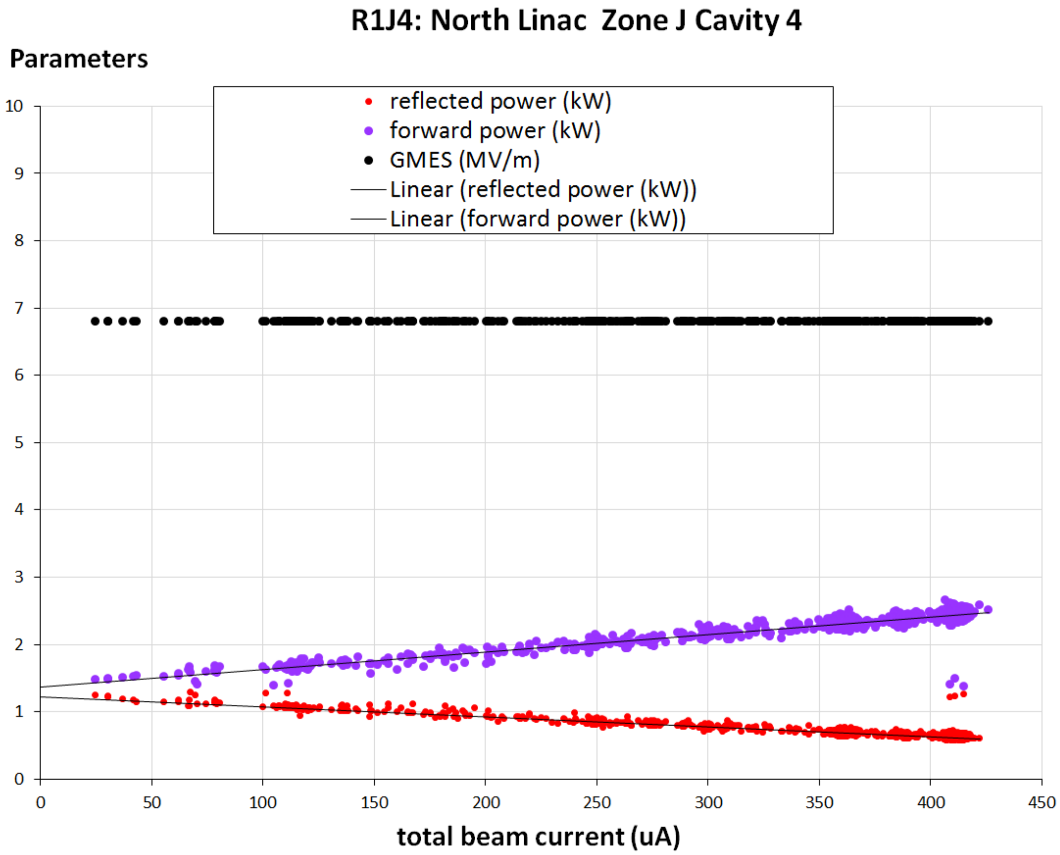
$$I_{tot} = \begin{pmatrix} Hall\ A\ injected\ I \\ Hall\ B\ injected\ I \\ Hall\ C\ injected\ I \\ Hall\ D\ injected\ I \end{pmatrix} \cdot \begin{pmatrix} passes\ to\ Hall\ A \\ passes\ to\ Hall\ B \\ passes\ to\ Hall\ C \\ 5 \end{pmatrix}^T$$

North linac with Hall D 6th pass in NL

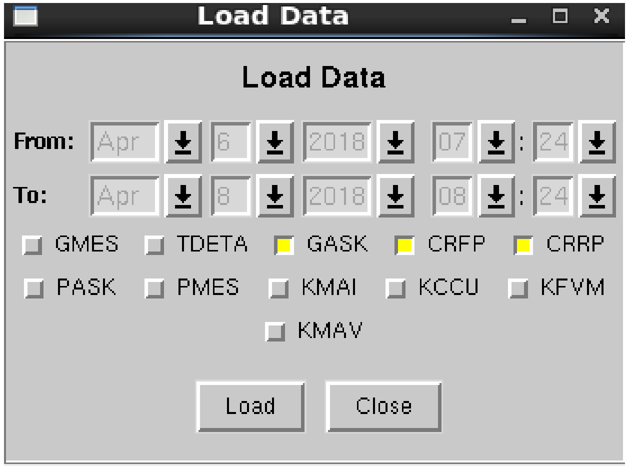
$$I_{tot} = \begin{pmatrix} Hall\ A\ injected\ I \\ Hall\ B\ injected\ I \\ Hall\ C\ injected\ I \\ Hall\ D\ injected\ I \end{pmatrix} \cdot \begin{pmatrix} passes\ to\ Hall\ A \\ passes\ to\ Hall\ B \\ passes\ to\ Hall\ C \\ 6 \end{pmatrix}^T$$

Example (1L19)

C20 cavity



- Used archived CEBAF data
- Time Stamping:
  2018/4/6 to 2018/4/8,
  when CEBAF beam current was ramped up
  Same period as used for G.A. Krafft's in a PIT meeting talk for C100 cavities



Load Data

From: Apr 6 2018 07 : 24

To: Apr 8 2018 08 : 24

☐ GMES ☐ TDETA ☑ GASK ☑ CRFP ☑ CRRP

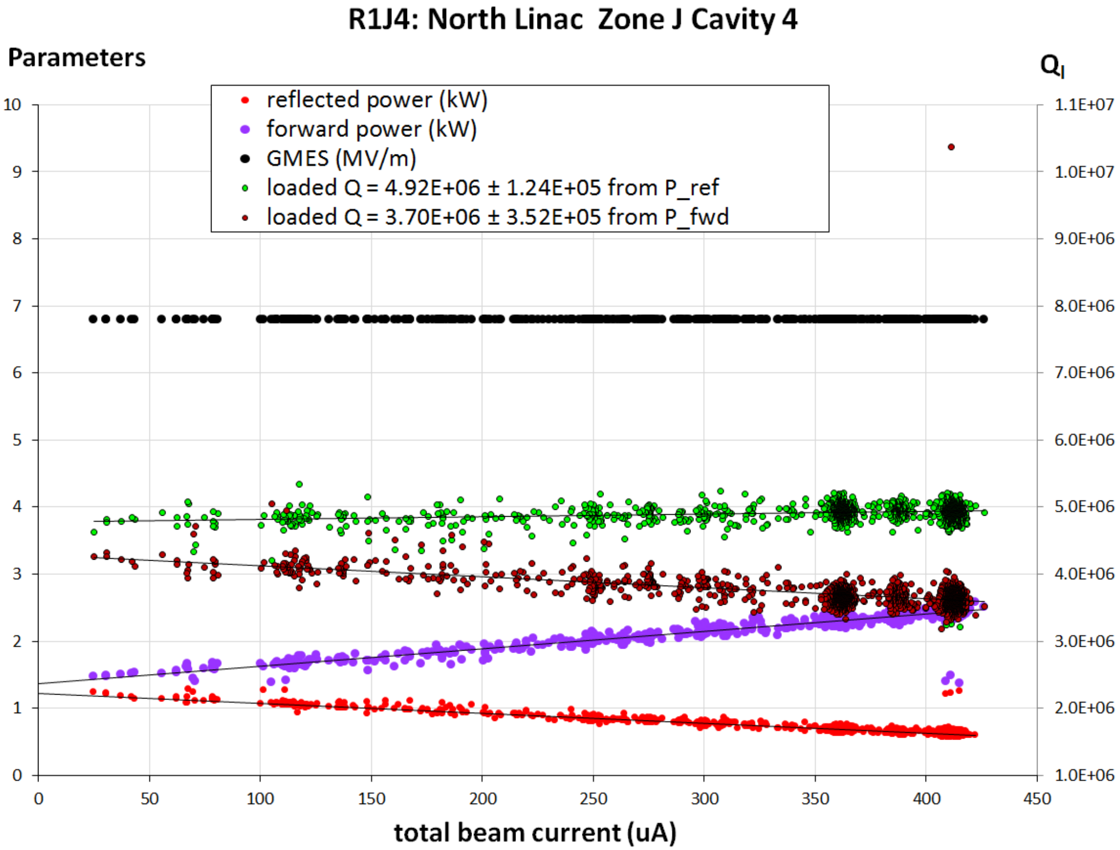
☐ PASK ☐ PMES ☐ KMAI ☐ KCCU ☐ KFVM

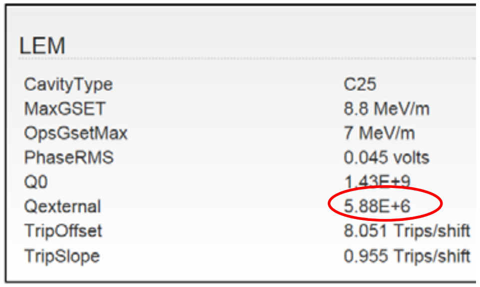
☐ KMAV

Example (1L19)

Mismatched cavity, no stub tuner installed → too small Q_l

C20 cavity





LEM

CavityType	C25
MaxGSET	8.8 MeV/m
OpsGsetMax	7 MeV/m
PhaseRMS	0.045 volts
Q0	1.43E+9
Qexternal	5.88E+6
TripOffset	8.051 Trips/shift
TripSlope	0.955 Trips/shift

Q_l from P_r

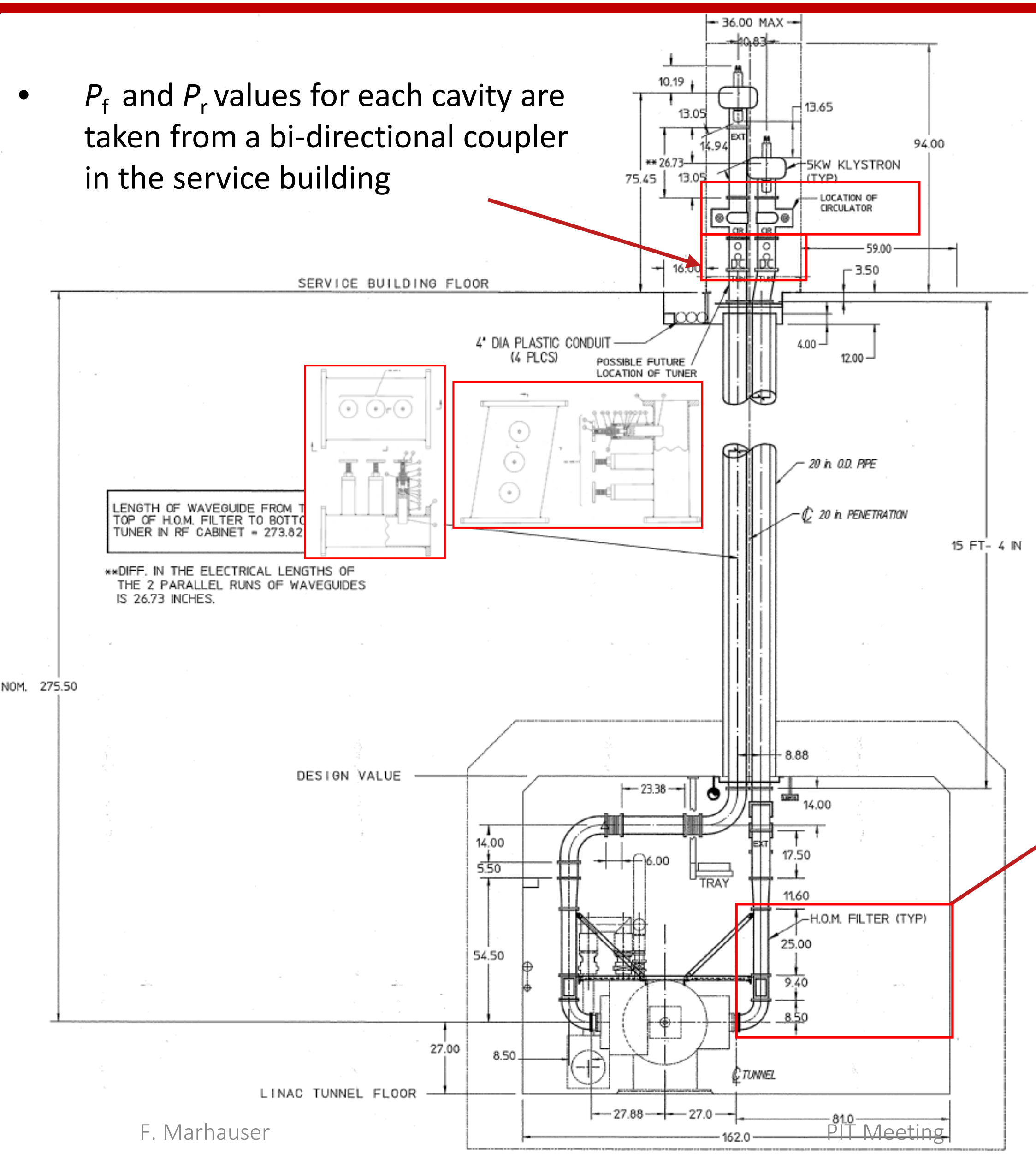
Q_l from P_f

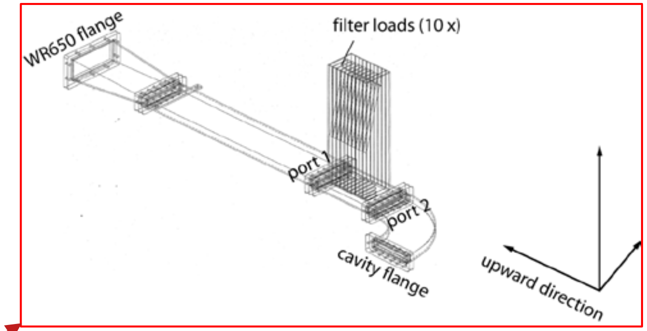
Why discrepancy ?

Accuracy of P_{fwd} and P_{ref}

- P_f and P_r values for each cavity are taken from a bi-directional coupler in the service building

- Though cables to the digital LLRF systems might be well calibrated, the losses in the power transmission line down to the cavities are not included





filter spec: insertion loss at 1497 ± 10 MHz	≤ 0.3 dB up to 5 kW CW maximally with both ports matched with VSWR 1.1:1 (-26.45 dB) or less
thermal load	64 Watts at 5 kW CW max. (loads are convection cooled)

Determination of Unknown Transmission Line Attenuation

$$Q_l\left(P_f, I_{tot}, V_c, \Psi, \frac{R}{Q}\right) = Q_l(P_r, I_{tot}, V_c, \Psi, \frac{R}{Q})$$

$$\frac{2P_f - I_{tot}V_c - 2P_f\sqrt{1 - \frac{I_{tot}V_c}{P_f} - \frac{I_{tot}{}^2 \cdot V_c{}^2}{4P_f{}^2}tan^2\Psi}}{{}^R/_Q I_{tot}{}^2} = \frac{2P_r + I_{tot}V_c - 2P_r\sqrt{1 + \frac{I_{tot}V_c}{P_r} - \frac{I_{tot}{}^2 \cdot V_c{}^2}{4P_r{}^2}tan^2\Psi}}{{}^R/_Q I_{tot}{}^2}$$

$$\boxed{2P_f - I_{tot}V_c - 2P_f\sqrt{1 - \frac{I_{tot}V_c}{P_f} - \frac{I_{tot}{}^2 \cdot V_c{}^2}{4P_f{}^2}tan^2\Psi} = 2P_r + I_{tot}V_c - 2P_r\sqrt{1 + \frac{I_{tot}V_c}{P_r} - \frac{I_{tot}{}^2 \cdot V_c{}^2}{4P_r{}^2}tan^2\Psi}}$$

- **To include attenuation α of transmission line (in dB): $P_f \cdot 10^{-\alpha/10}$**
- **For reflected power: $P_r \cdot 10^{(\alpha-\gamma)/10}$, γ (dB) = eventual calibration error of 'stamped' BC**

$$2P_f \cdot 10^{-\alpha/10} - I_{tot}V_c - 2P_f \cdot 10^{-\alpha/10}\sqrt{1 - \frac{I_{tot}V_c}{P_f} - \frac{I_{tot}{}^2 \cdot V_c{}^2}{4P_f{}^2}tan^2\Psi} =$$

$$2P_r \cdot 10^{(\alpha-\gamma)/10} + I_{tot}V_c - 2 \cdot 10^{(\alpha-\gamma)/10}\sqrt{1 + \frac{I_{tot}V_c}{P_r} - \frac{I_{tot}{}^2 \cdot V_c{}^2}{4P_r{}^2}tan^2\Psi}$$

Determination of Unknown Transmission Line Attenuation

$$2P_f \cdot 10^{-\alpha/10} - I_{tot}V_c - 2P_f \cdot 10^{-\alpha/10}\sqrt{1 - \frac{I_{tot}V_c}{P_f} - \frac{{I_{tot}}^2 \cdot {V_c}^2}{4{P_f}^2}tan^2\Psi} =$$
$$2P_r \cdot 10^{(\alpha-\gamma)/10} + I_{tot}V_c - 2P_r \cdot 10^{(\alpha-\gamma)/10}\sqrt{1 + \frac{I_{tot}V_c}{P_r} - \frac{{I_{tot}}^2 \cdot {V_c}^2}{4{P_r}^2}tan^2\Psi}$$

Substitution: $Att = 10^{\alpha(dB)/10}$ **(attenuation factor)**

Sorting:

$$Att^2 - \frac{I_{tot}V_c \cdot Att}{P_r \cdot 10^{-\frac{\gamma}{10}}\left(\sqrt{1+\frac{I_{tot}V_c}{P_r}-\frac{{I_{tot}}^2 \cdot {V_c}^2}{4{P_r}^2}tan^2\Psi}-1\right)} - \frac{P_f\left(\sqrt{1-\frac{I_{tot}V_c}{P_f}-\frac{{I_{tot}}^2 \cdot {V_c}^2}{4{P_f}^2}tan^2\Psi}-1\right)}{P_r \cdot 10^{-\frac{\gamma}{10}}\left(\sqrt{1+\frac{I_{tot}V_c}{P_r}-\frac{{I_{tot}}^2 \cdot {V_c}^2}{4{P_r}^2}tan^2\Psi}-1\right)} = 0$$

Solution:

$$Att = \frac{I_{tot}V_c \boxed{\pm} \sqrt{(I_{tot}V_c)^2 + 4P_f \cdot P_r \cdot 10^{-\frac{\gamma}{10}}\left(\sqrt{1 - \frac{I_{tot}V_c}{P_f} - \frac{{I_{tot}}^2 \cdot {V_c}^2}{4{P_f}^2}tan^2\Psi} - 1\right)\left(\sqrt{1 + \frac{I_{tot}V_c}{P_r} - \frac{{I_{tot}}^2 \cdot {V_c}^2}{4{P_r}^2}tan^2\Psi} - 1\right)}}{2P_r \cdot 10^{-\frac{\gamma}{10}}\left(\sqrt{1 + \frac{I_{tot}V_c}{P_r} - \frac{{I_{tot}}^2 \cdot {V_c}^2}{4{P_r}^2}tan^2\Psi} - 1\right)}$$

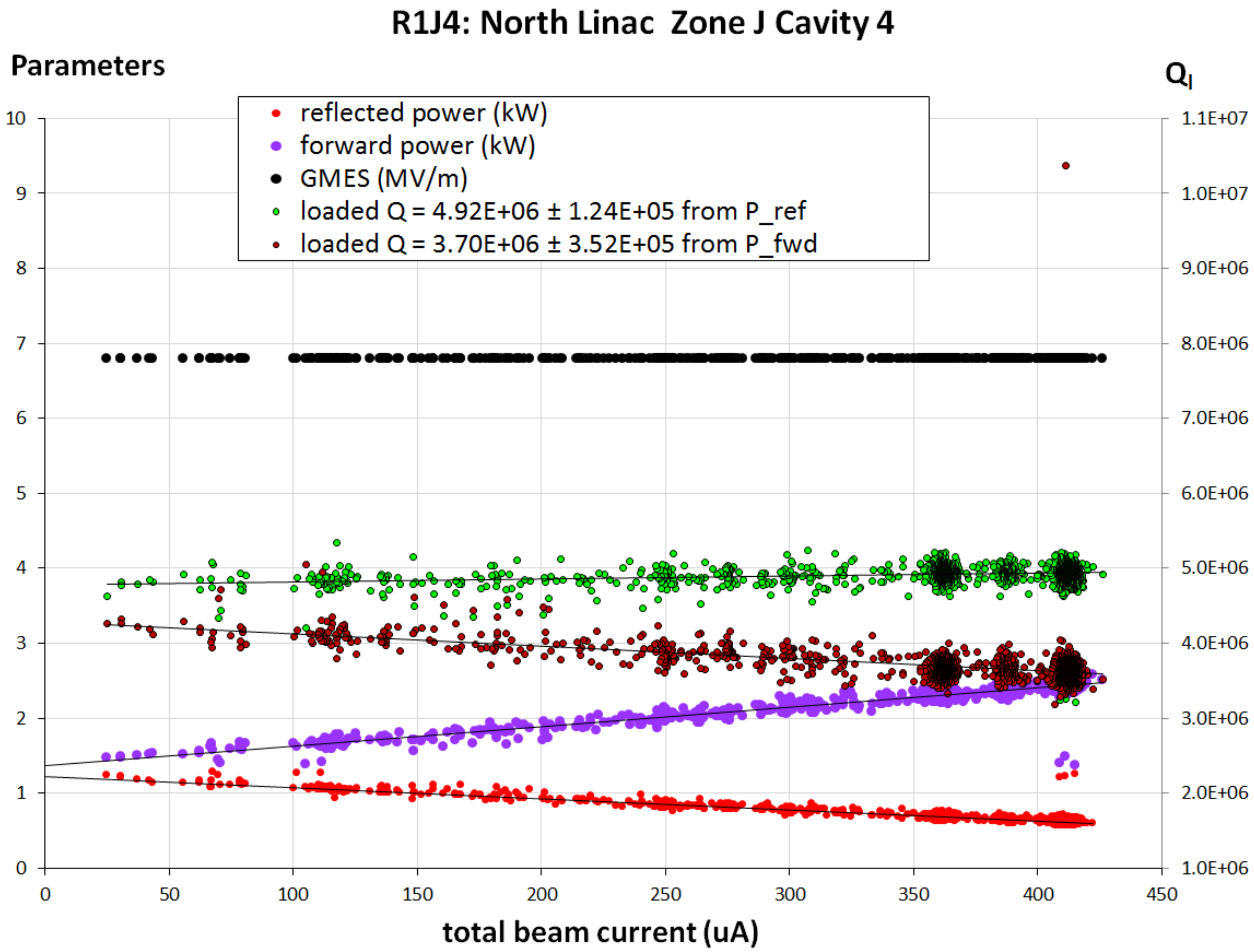
Attenuation is: $\alpha(dB) = 10 \cdot Log10(Att)$

only negative sign is valid

instantenous calibration

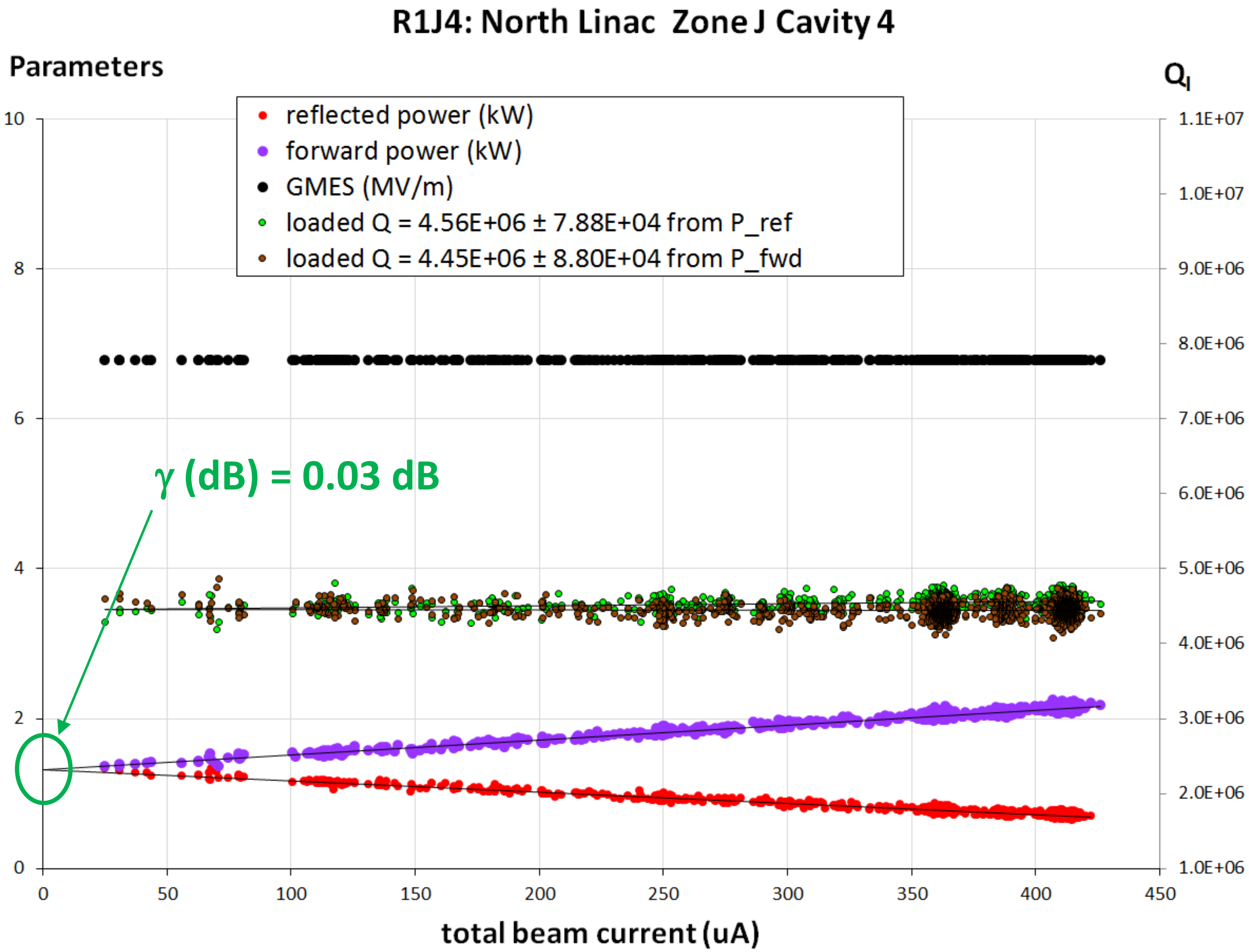
Example (1L19-4)

Before Correction:



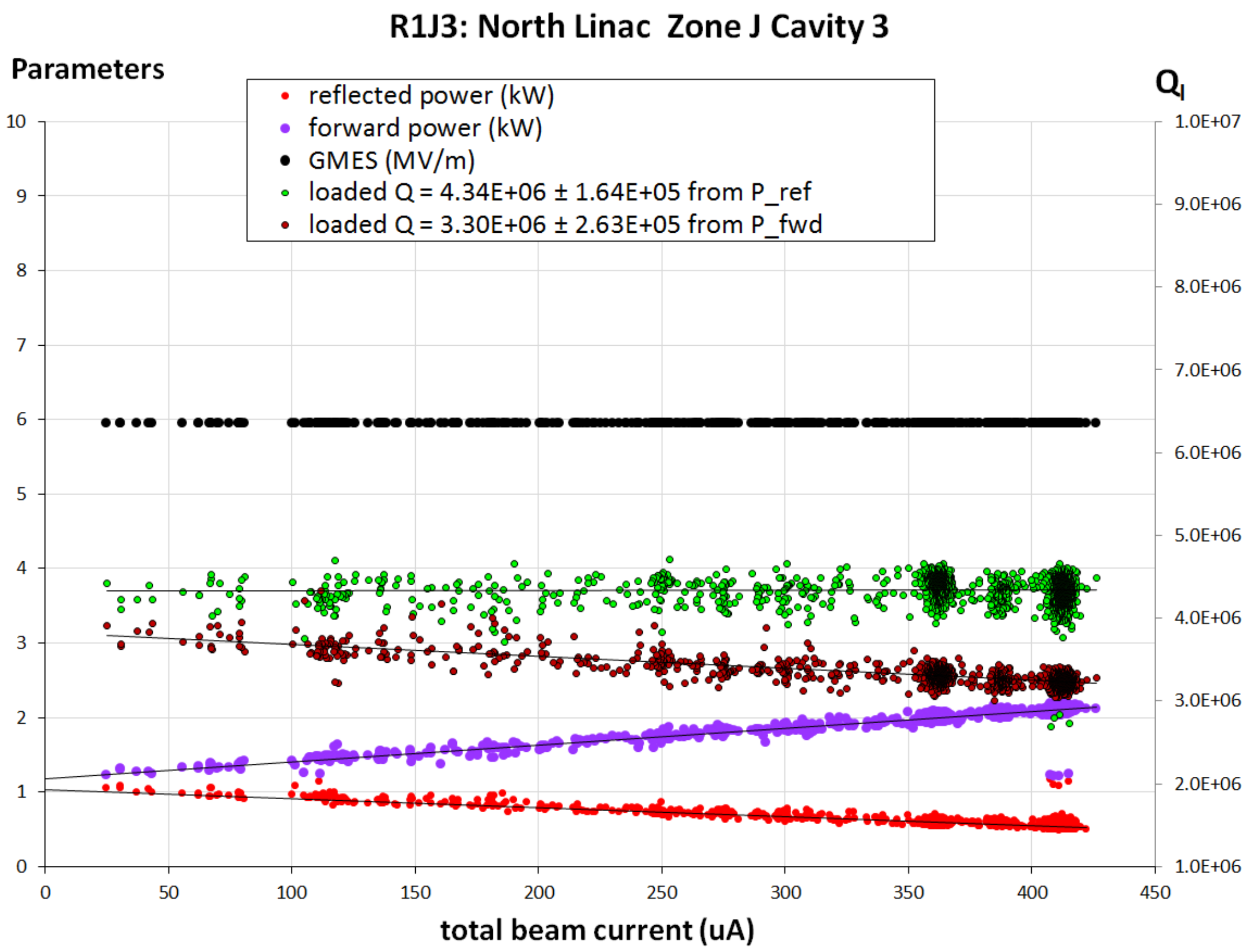
Example (1L19-4)

After Correction:



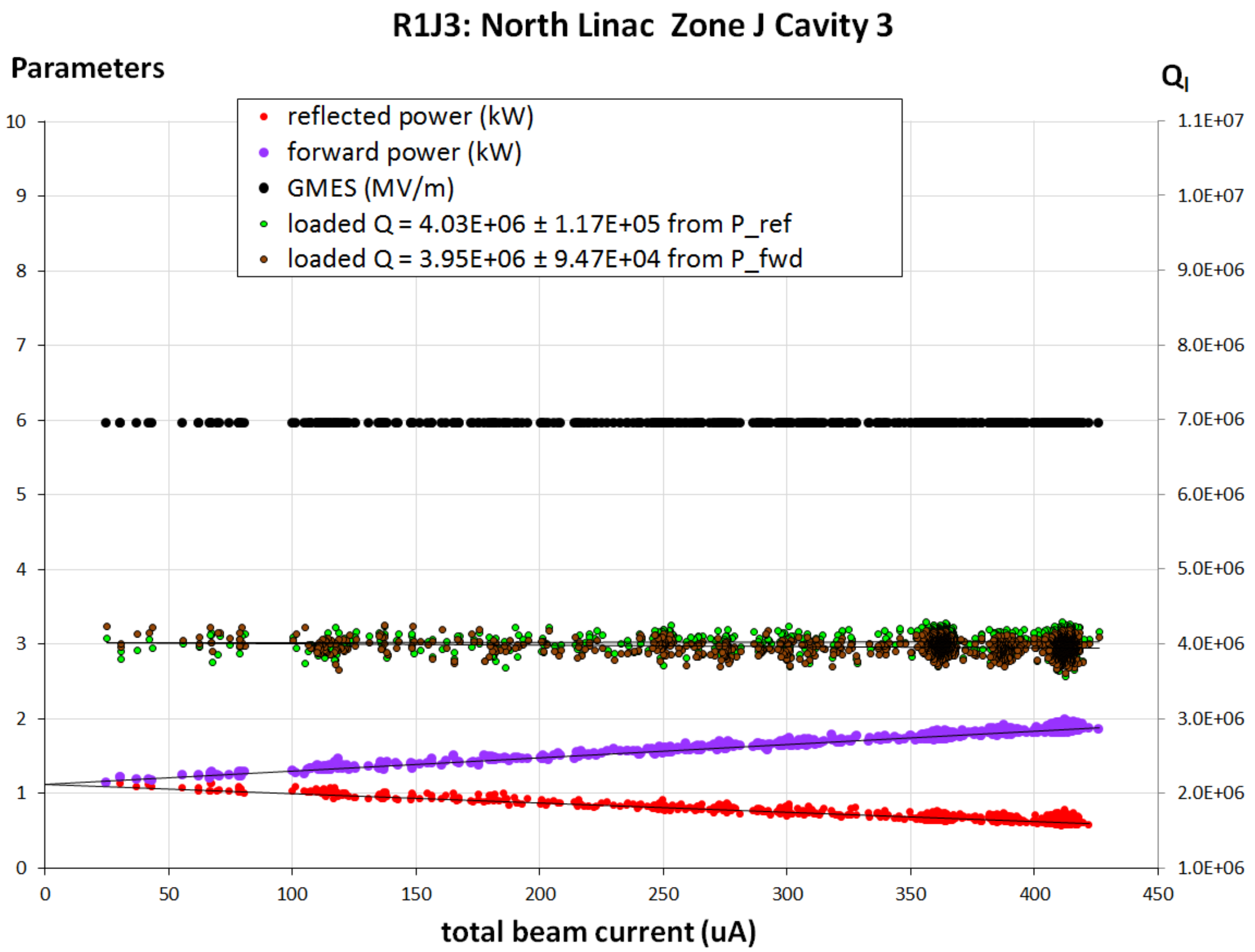
Example

Before Correction:



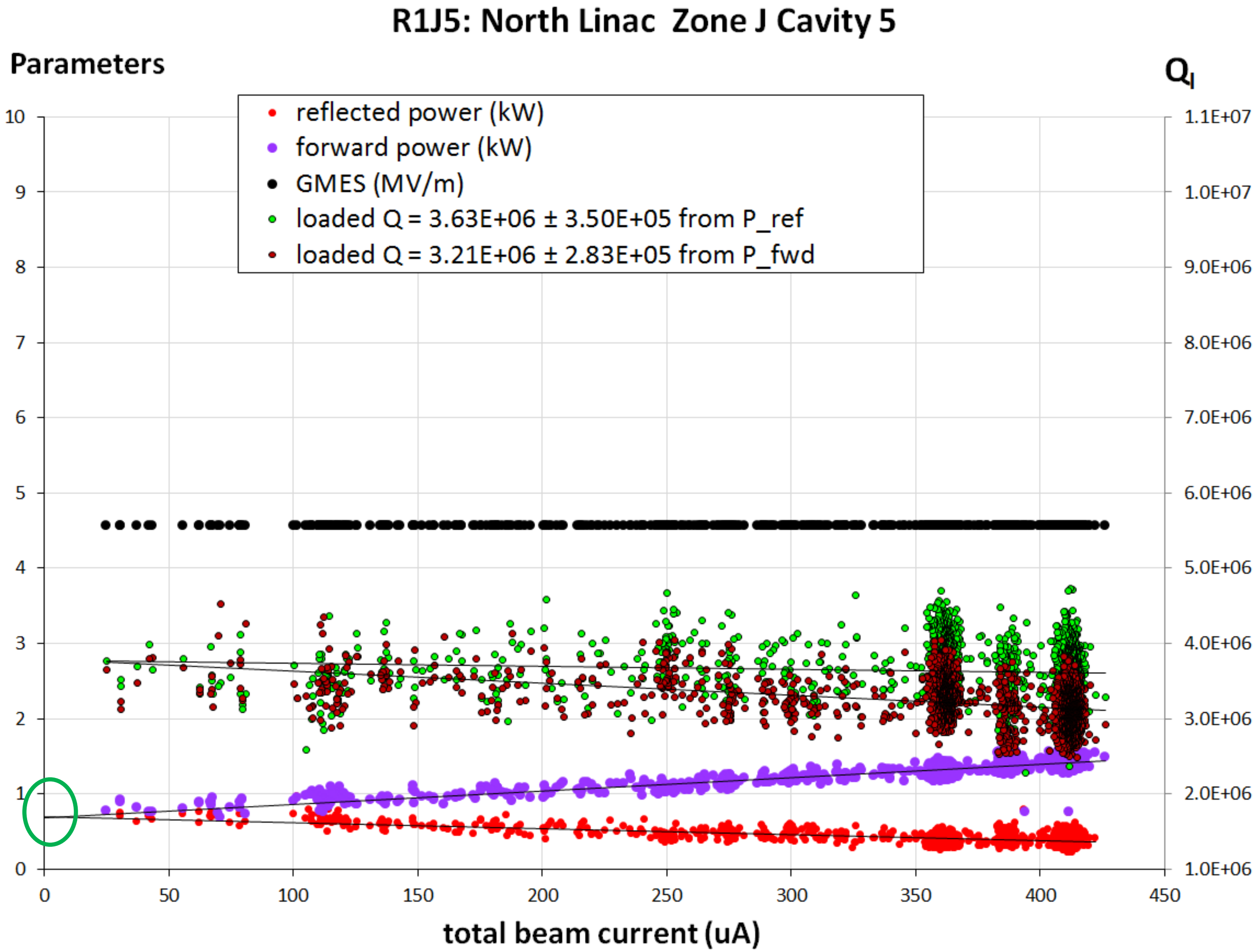
Example

After Correction: γ **(dB) = 0.03 dB**



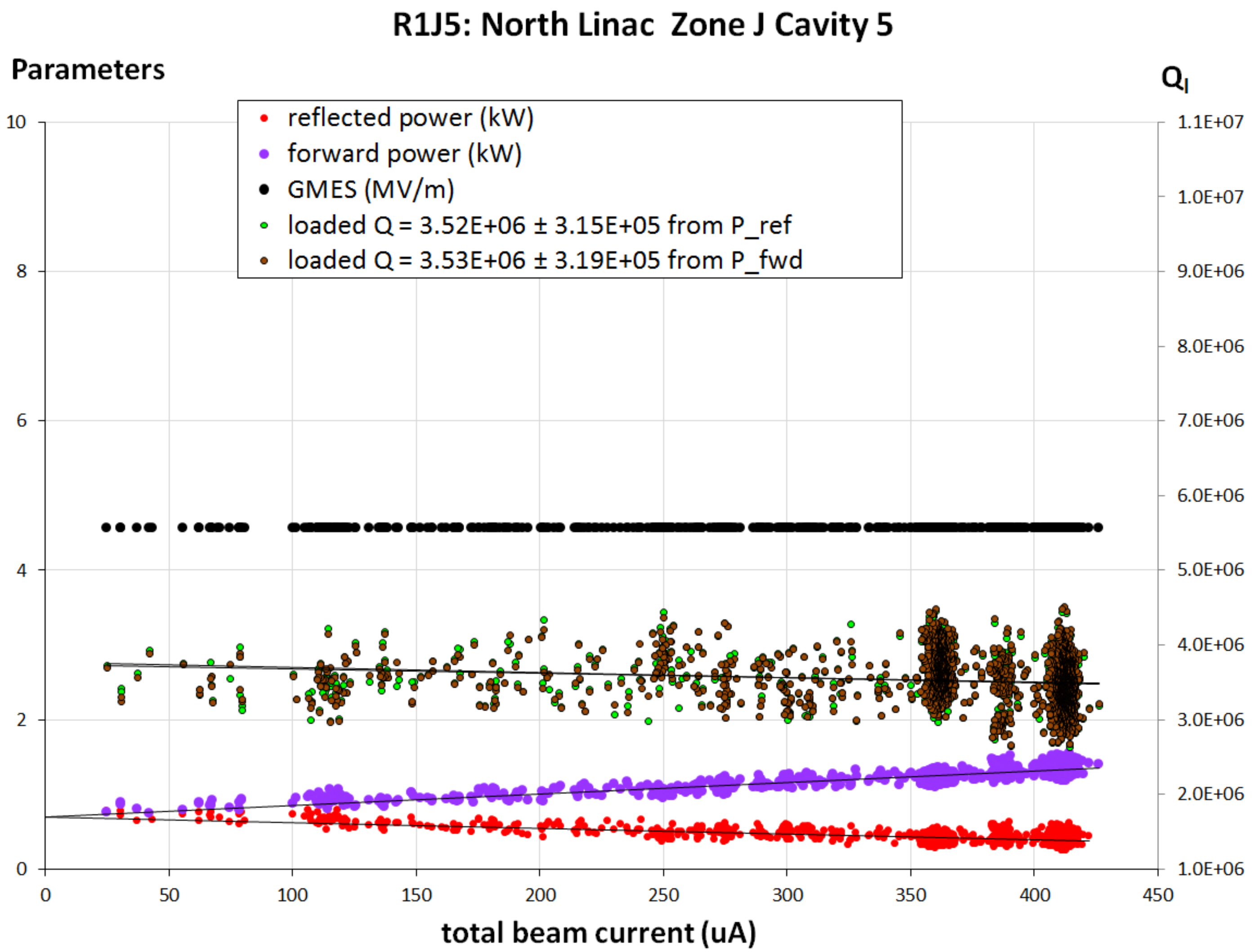
Example

Before Correction:



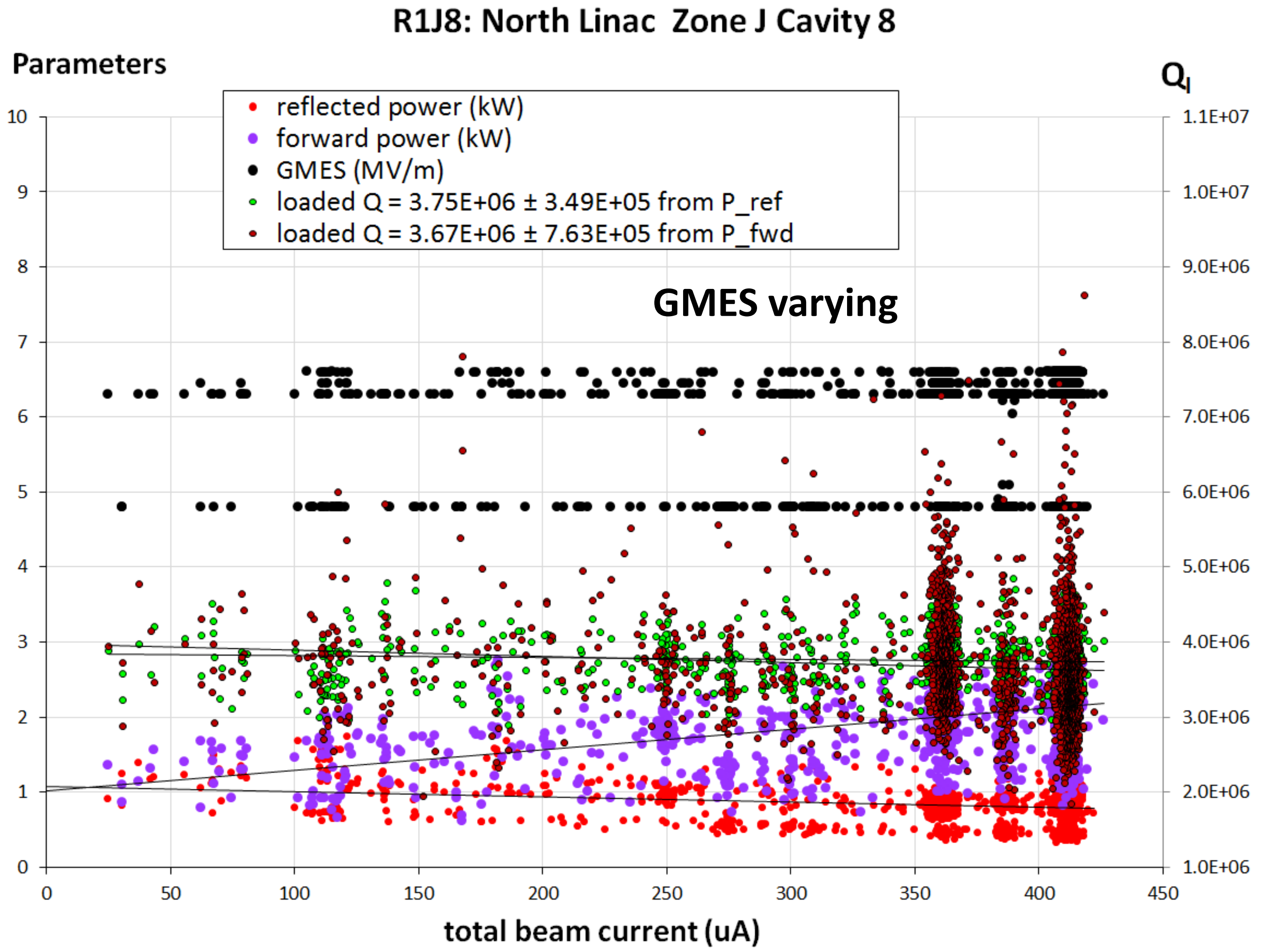
Example

After Correction: γ **(dB) = 0 dB**



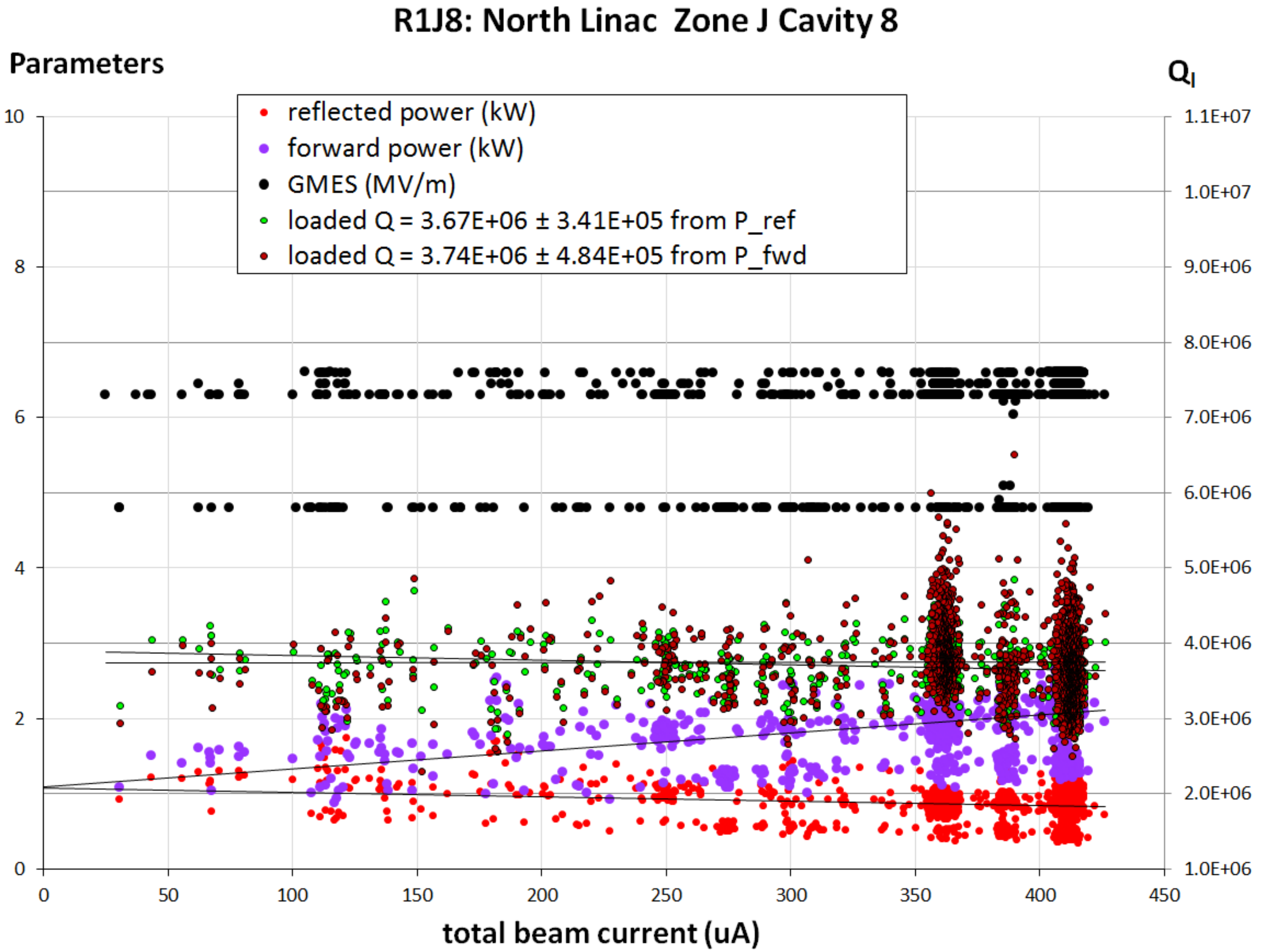
Example

Before Correction:



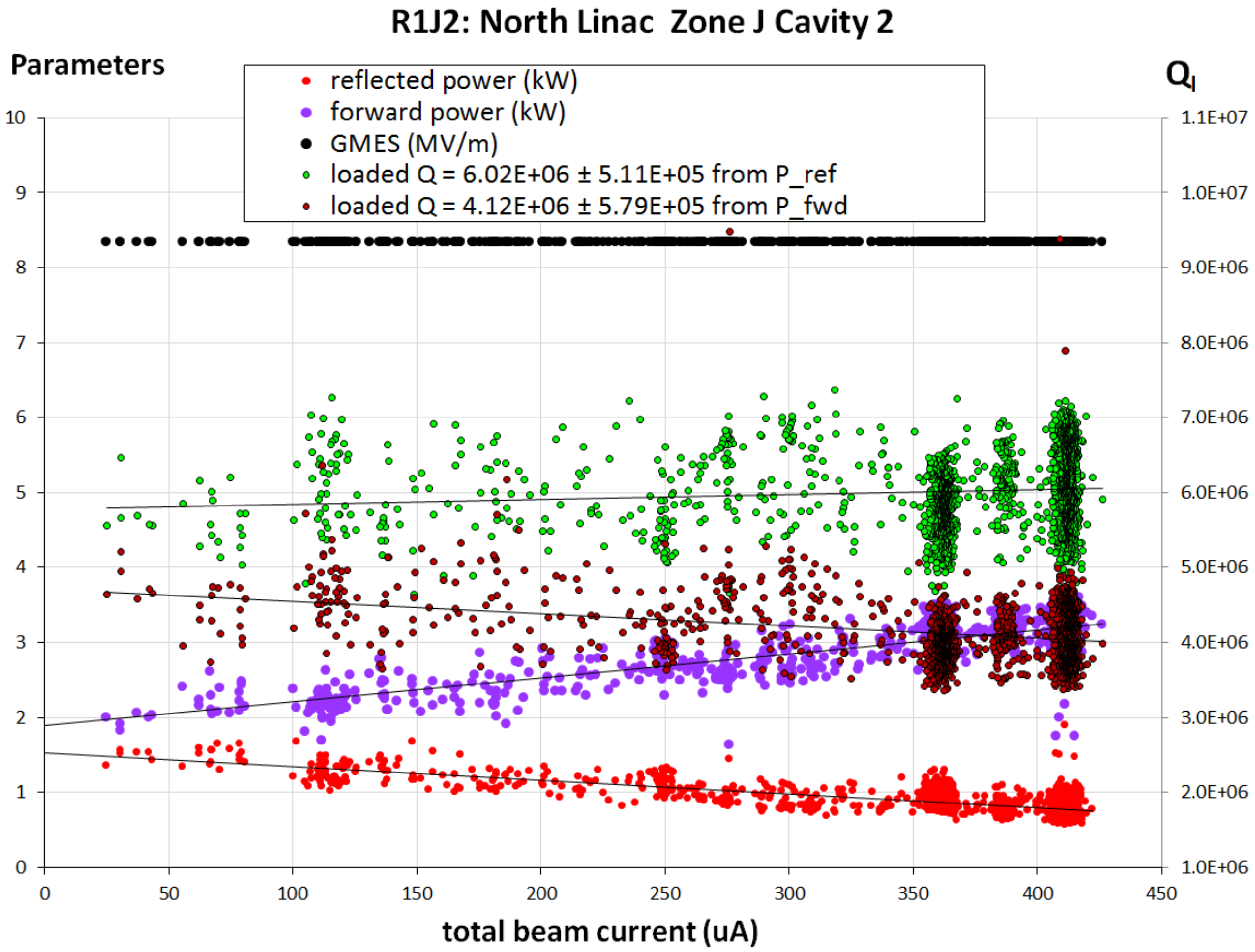
Example

After Correction: γ (dB) = 0 dB



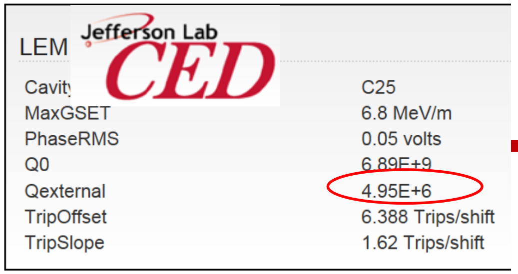
Example

Before Correction:



} ~1 kW fwd. power fluctuations !

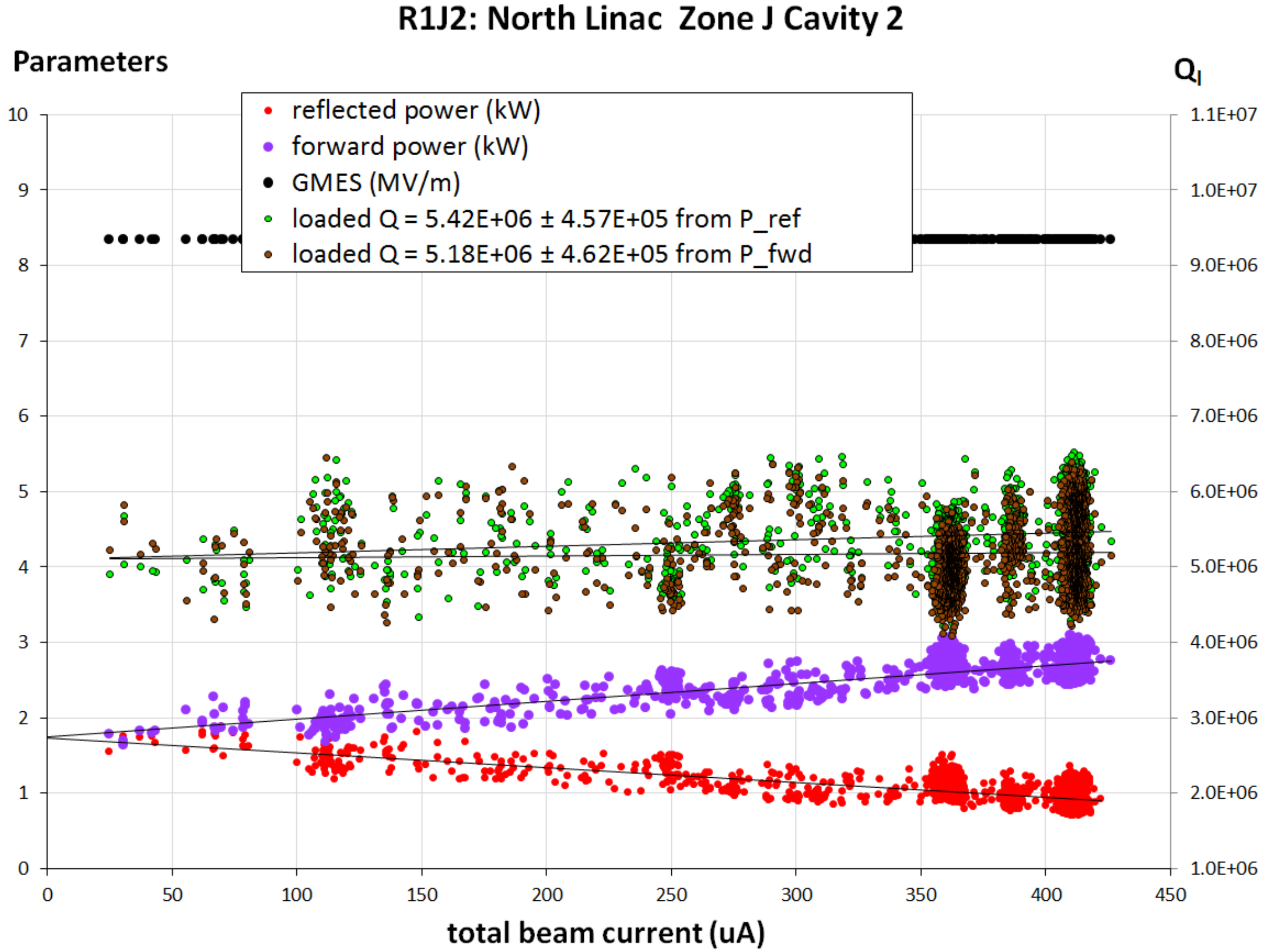
Example



LEM

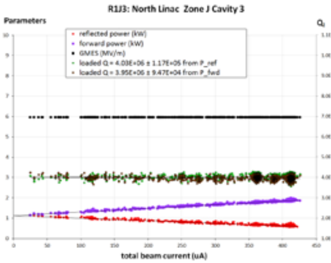
Cavit	C25
MaxGSET	6.8 MeV/m
PhaseRMS	0.05 volts
Q0	6.89E+9
Qexternal	4.95E+6
TripOffset	6.388 Trips/shift
TripSlope	1.62 Trips/shift

After Correction: γ (dB) = 0.07 dB

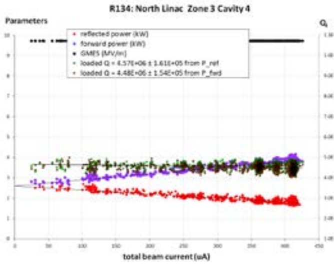


More Examples: NL (C20/C50 CMs)

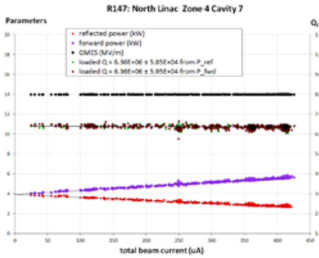
R13 – C20



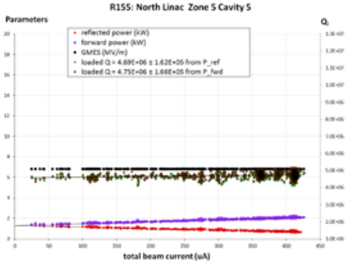
R14 – C20



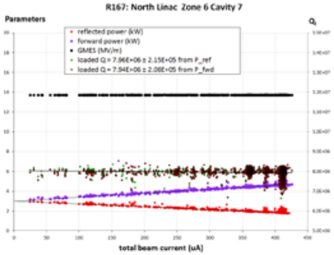
R14 – C50



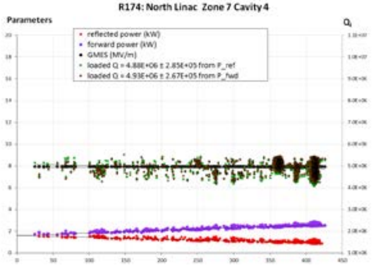
R15 – C50



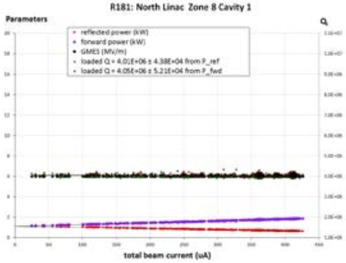
R16 – C50



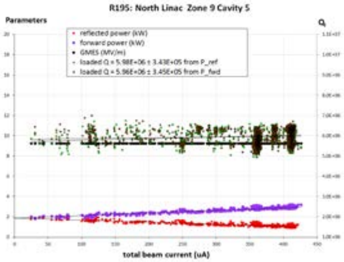
R17 – C20



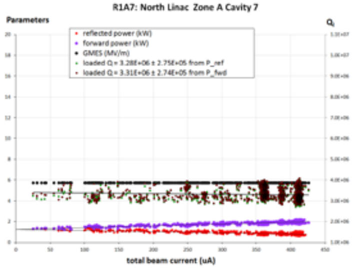
R18 – C20



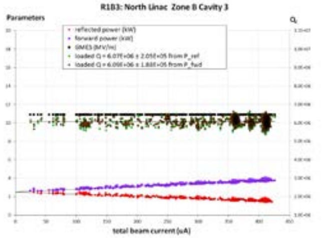
R19 – C20



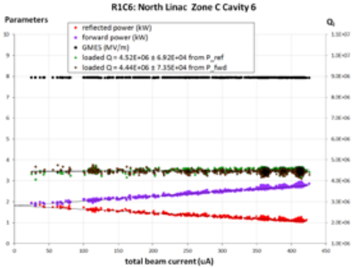
R1A – C20



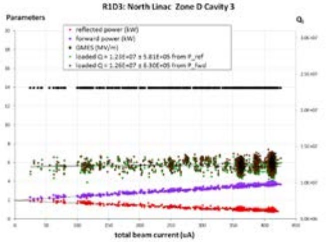
R1B – C50



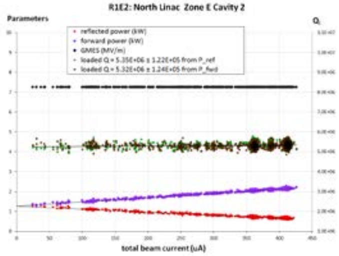
R1C – C50



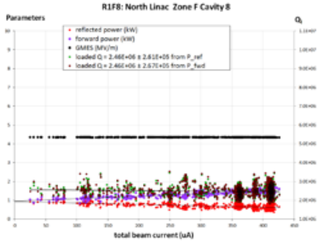
R1D – C50 (incl. C75)



R1E – C20

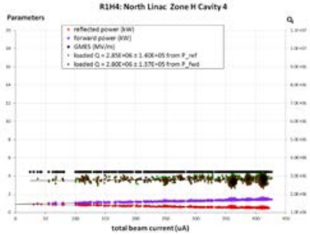


R1F – C20

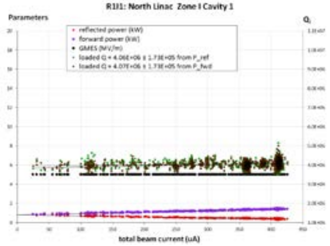


R1G – C20

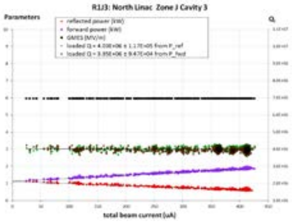
R1H – C20



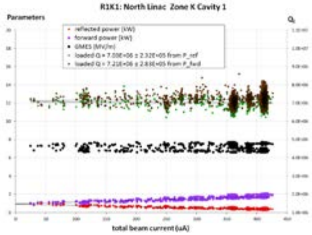
R1I – C20



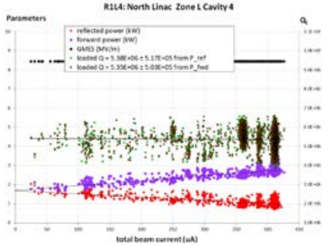
R1J – C20



R1K – C20

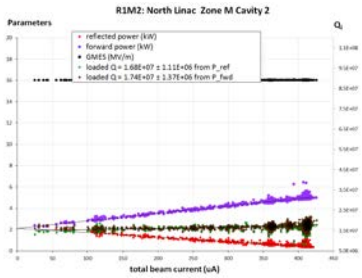


R1L – C20

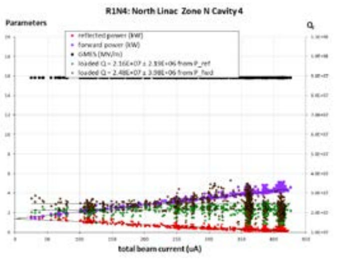


More Examples: NL (C100 CMs)

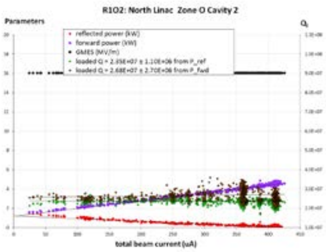
R1M – C100



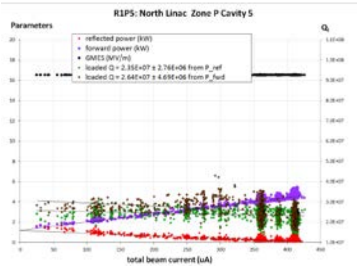
R1N – C100



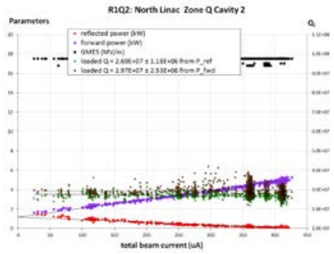
R1O – C100



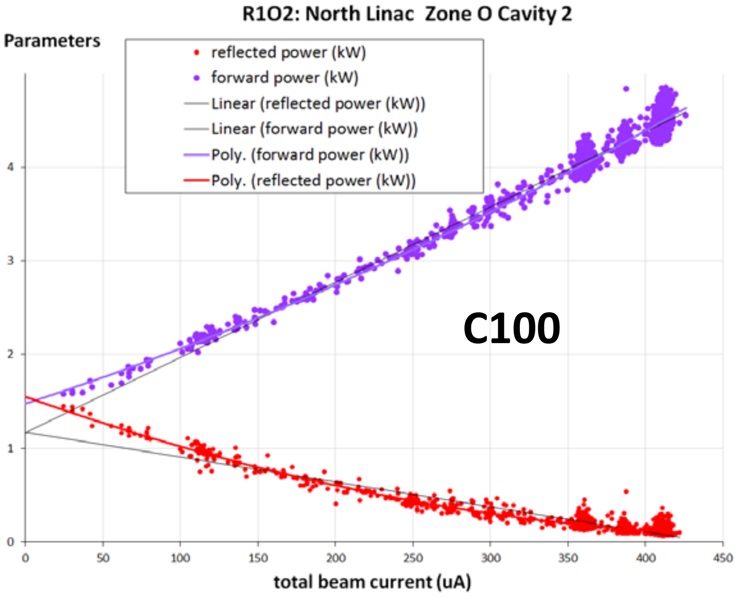
R1P – C100

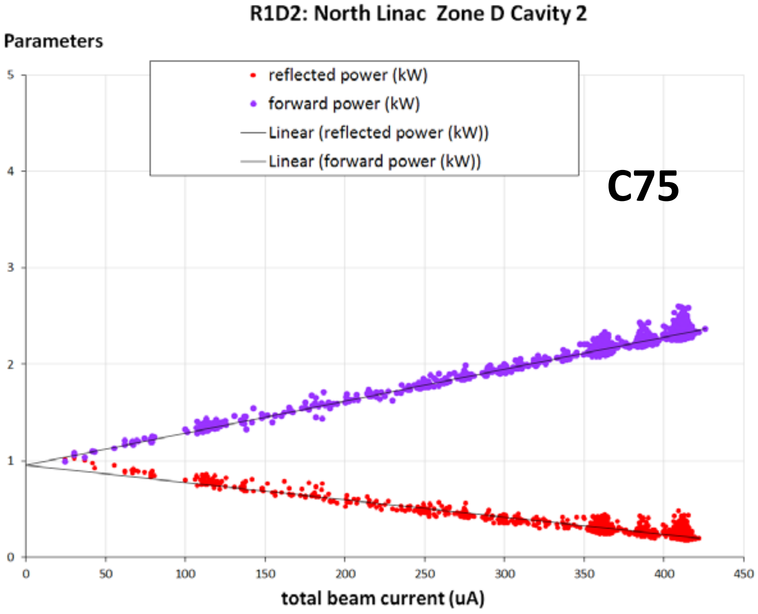


R1Q – C100



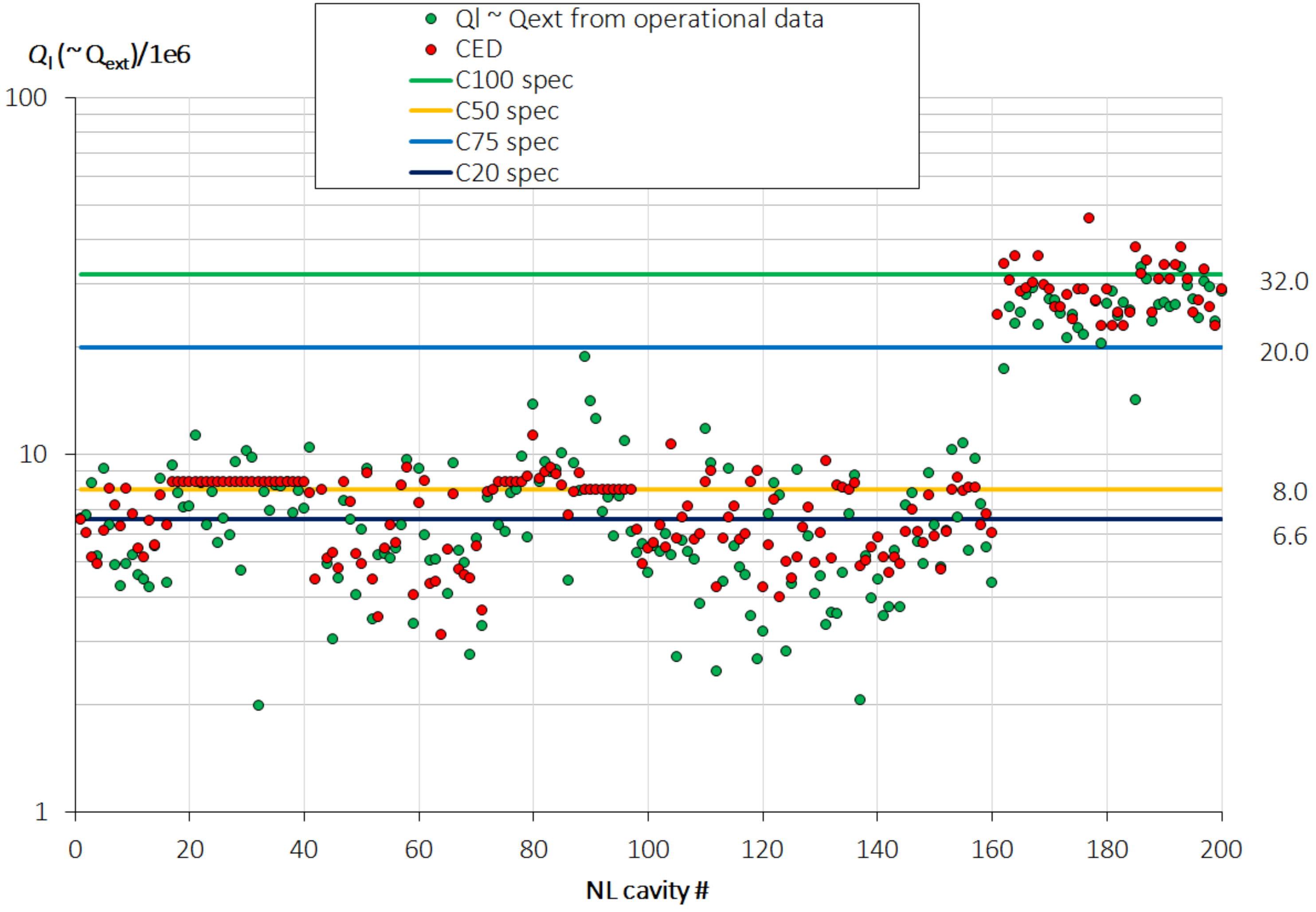
- Typical non-linear behavior of P_f and P_r observed for C100 cavities





North Linac

Comparison and Update of CED Data



F. Marhauser

Summary

- **Instantaneous Q_l (Q_{ext}) measurements possible with instantaneous power transmission line calibration**
- **Could be applied for other accelerators, and those with adjustable tuners to verify coupling online**
- **Use as diagnostic tool? E.g. calibration issues…**
- **Can missing calibration explain CEBAF energy 'fudge factor'?** Per Arne: Nominally 1-2 % but "…SRF calibration can sometimes be off by 5-10%."
- **Plan forward: Implement new method into EPICS at CEBAF using highly synchronized parameters available from digital RF system**
  - talked already to Tomasz Plawski to get started…
- **TDB: Identifying worst mismatched cavities and tuning Q_l…**