Advanced RF Design and Tuning Methods of RFQ for High Intensity Proton Linacs

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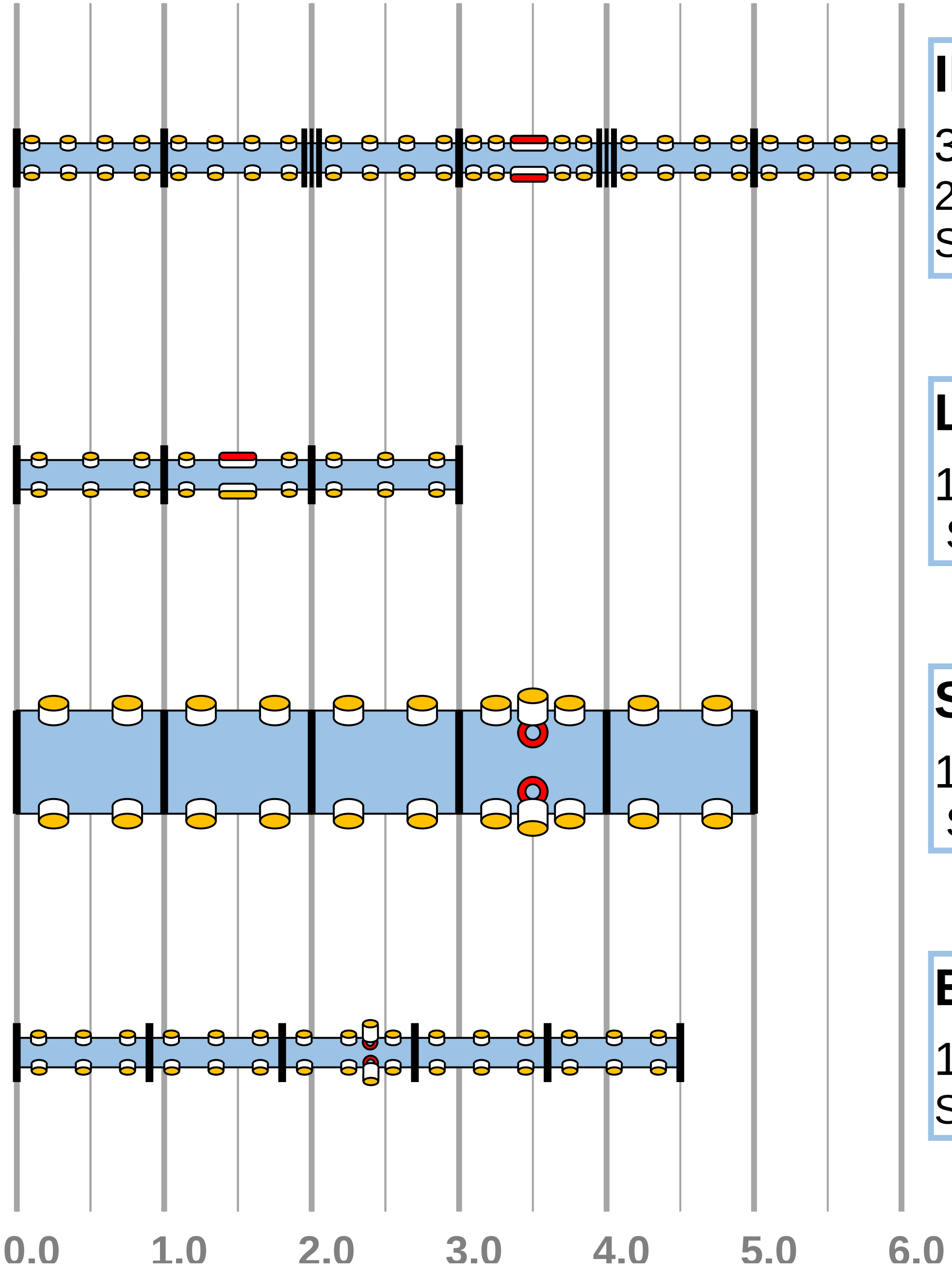
MOZA02

Contents

1. Introduction and Theoretical Framework

Our RFQ Projects for High Intensity Linacs



IPHI 352.2 MHz 6.0 m 100 mA CW 3 MeV

3 coupled segments of
2 brazed modules each
Status: tuned, start commissioning 2014 Q3

4 iris + qwt **96 tuners**

LINAC4 352.2 MHz 3.0 m 80 mA 7.5% 3 MeV

1 segments of 3 brazed modules
Status: operational

1 iris + qwt **32 tuners**

SPIRAL2 88.05 MHz 5.0 m 5 mA CW 3 MeV

1 segment of 5 bolted modules
Status: start tuning 2014 Q3

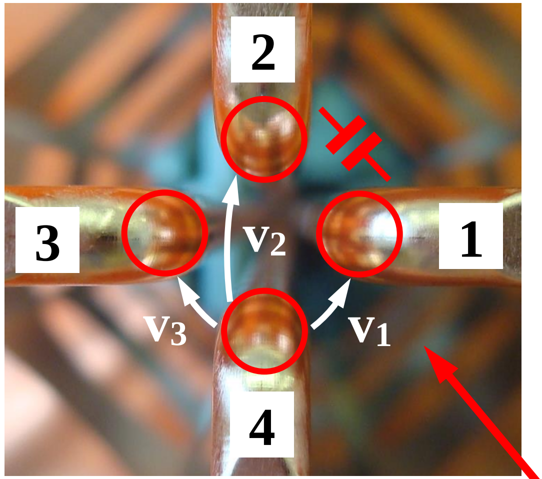
4 loops **40 tuners**

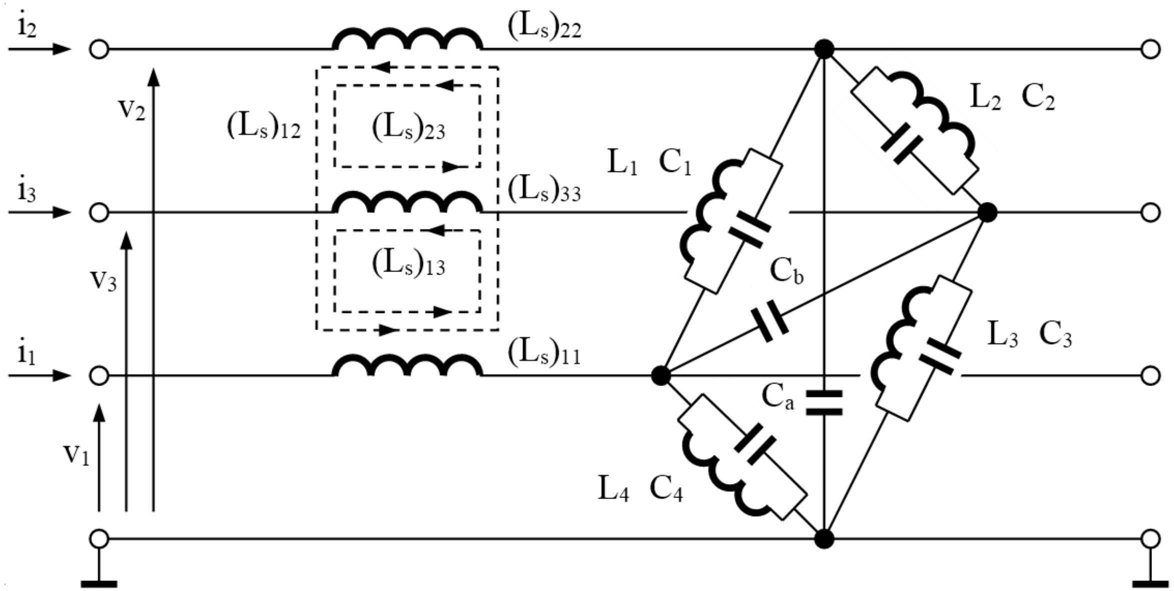
ESS 352.2 MHz 4.5 m 62.5 mA 4% 3.6 MeV

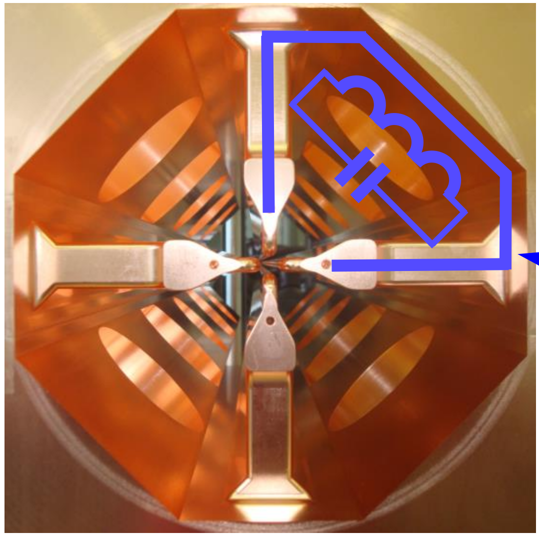
1 segment of 5 brazed modules
Status: design completed 2014 Q3

2 loops **60 tuners**

The Loaded Lossless 4-Wire Transmission Line Model (TLM)







Axial region: $H_z \approx 0$, TEM 4-wire line

4 capacitances between adjacent electrodes C_1 to C_4 (F/m)

2 capacitances between opposite electrodes C_a, C_b (F/m)

fundamental TEM relation: $\nu^2 L_s C = I$

Quadrants are $\lambda/4$ resonators

complement with 4 inductances L_1 to L_4 (H.m)

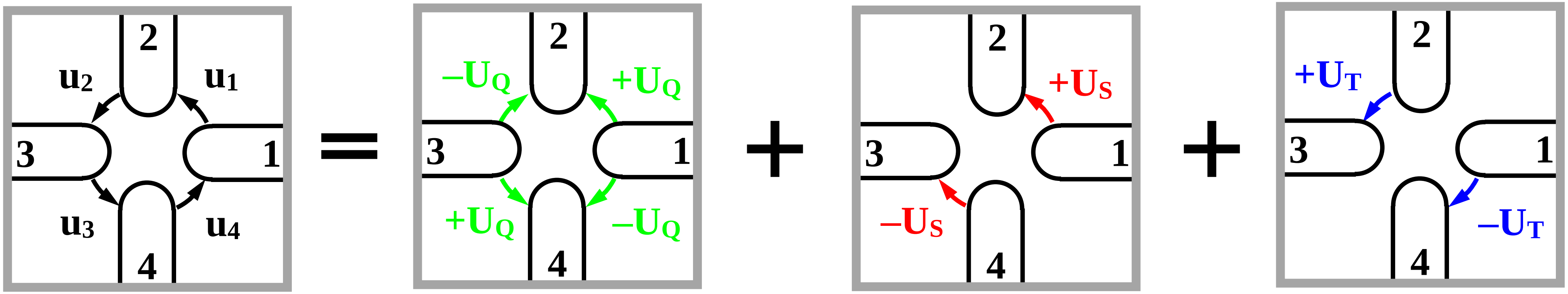
Transmission line equation (dim. 3, since three cuts make the system of conductors simply connected) :

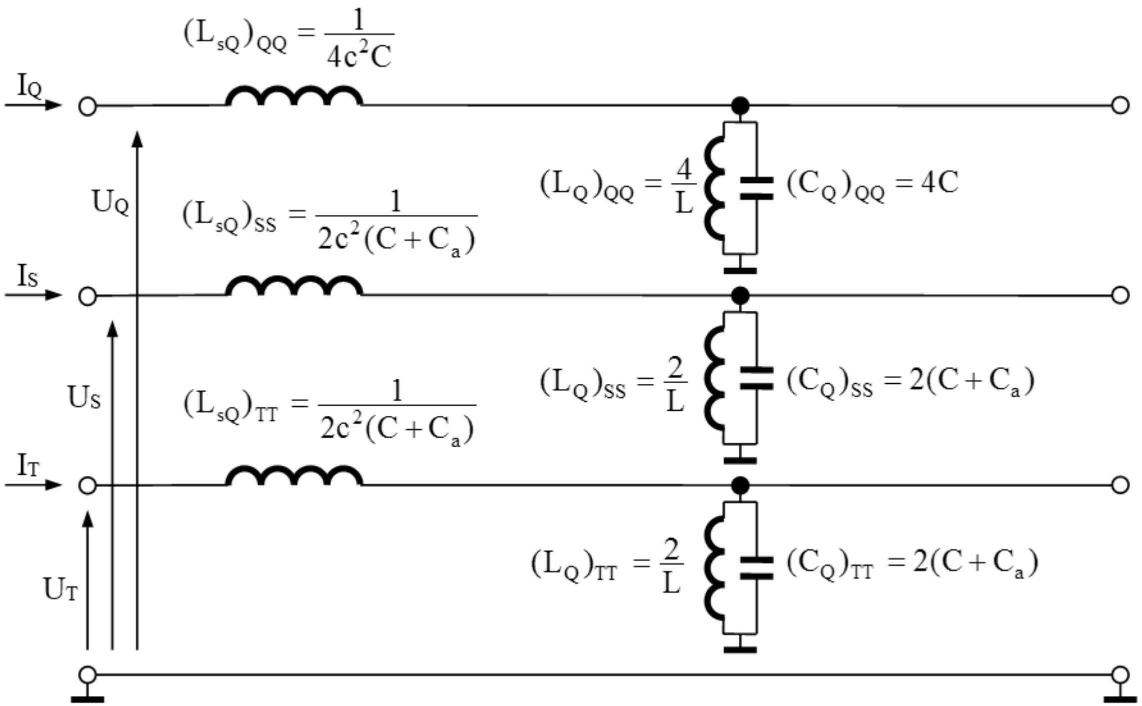
$$-\frac{\partial}{\partial z}\left(C\frac{\partial v}{\partial z}\right) + \frac{1}{\nu^2} L v = \frac{\omega^2}{\nu^2} C v$$

The TLM Canonical Basis {Q,S,T}

Quadrupole-like subspace

Dipole-like subspace (dim. 2)





$$-\frac{\partial}{\partial z}\left(C_Q \frac{\partial U}{\partial z}\right) + \frac{1}{\nu^2} L_Q\, U = \frac{\omega^2}{\nu^2} C_Q\, U$$

For an ideal (quaternary-symmetric) RFQ:

C_Q & L_Q are diagonal

Q, S & T are decoupled

TLM Boundary Conditions

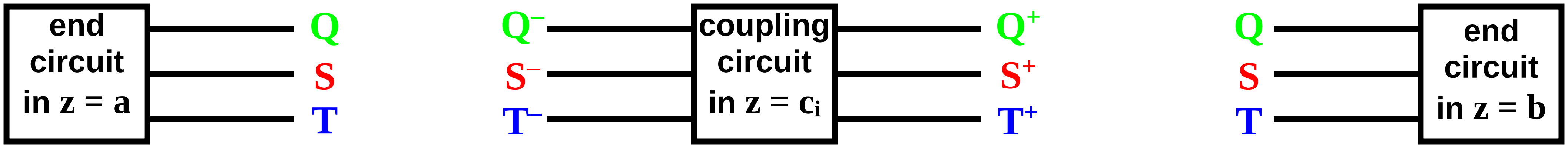
arbitrary reciprocal lossless circuits, defined in {Q,S,T} basis
by their admittance matrixes (which are assumed to exist)

circuit theory: admittance matrixes y_a y_{ci} y_b

$$I(a) = -y_a\, U(a)$$

$$\begin{vmatrix} I(c_i^-) \\ -I(c_i^+) \end{vmatrix} = y_{c_i} \begin{vmatrix} U(c_i^-) \\ U(c_i^+) \end{vmatrix}$$

$$I(b) = +y_b\, U(b)$$



transmission line theory: s-matrixes s_a s_{ci} s_b

$$\frac{\partial U(a)}{\partial z} = -s_a\, U(a)$$

$$\begin{vmatrix} \dfrac{\partial U(c_i^-)}{\partial z} \\ -\dfrac{\partial U(c_i^+)}{\partial z} \end{vmatrix} = +s_{c_i} \begin{vmatrix} U(c_i^-) \\ U(c_i^+) \end{vmatrix}$$

$$\frac{\partial U(b)}{\partial z} = +s_b\, U(b)$$

$$s_a = -j\omega\, L_{sQ}(a)\; y_a$$

$$s_{c_i} = -j\omega \begin{vmatrix} L_{sQ}(c_i^-) & 0 \\ 0 & L_{sQ}(c_i^+) \end{vmatrix} y_{c_i}$$

$$s_b = -j\omega\, L_{sQ}(b)\; y_b$$

TLM Properties (1/3)

The TLM takes the form of a vector regular Sturm-Liouville problem

Linear operator $\mathcal{L}$:

U satisfies boundary conditions,

$$\mathcal{L}\,U = -C_Q^{-1}\frac{\partial}{\partial z}\left(C_Q\frac{\partial U}{\partial z}\right) + \frac{1}{\nu^2}C^{-1}L_Q\,U$$

Eigenvalue problem

$$\mathcal{L}\,U = \frac{\omega^2}{\nu^2}U$$

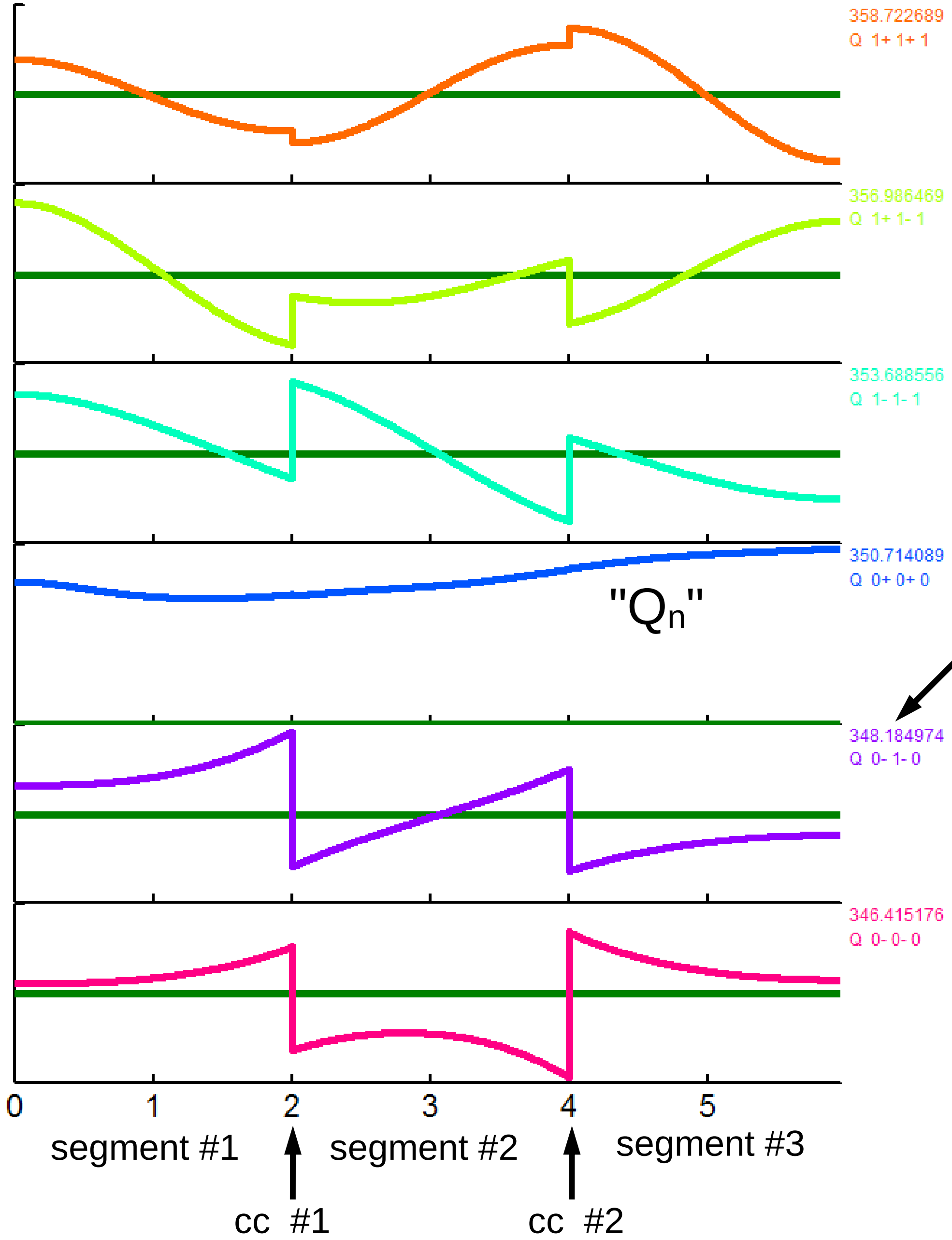
$\mathcal{L}$ is un-bounded, with bounded compact inverse, and is self-adjoint for the inner-product

$$\langle u, v\rangle = \int_\Omega v^* C_Q u\,dz$$ (with given boundary conditions)

three subsets Q, S and T of countable eigenpairs

$$\left\{\omega_{Q_i}, V_{Q_i}(z) = \begin{vmatrix} V_{Q_i,Q}(z) \\ V_{Q_i,S}(z) \\ V_{Q_i,T}(z) \end{vmatrix}\right\} \quad \left\{\omega_{S_j}, V_{S_j}(z) = \begin{vmatrix} V_{S_j,Q}(z) \\ V_{S_j,S}(z) \\ V_{S_j,T}(z) \end{vmatrix}\right\} \quad \left\{\omega_{T_k}, V_{T_k}(z) = \begin{vmatrix} V_{T_k,Q}(z) \\ V_{T_k,S}(z) \\ V_{T_k,T}(z) \end{vmatrix}\right\}$$

TLM Properties (2/3)



for an ideal (quaternary-symmetric) RFQ

$$V_{Q_i} = \begin{vmatrix} V_{Q_i,Q} \\ 0 \\ 0 \end{vmatrix} \qquad V_{S_j} = \begin{vmatrix} 0 \\ V_{S_j,S} \\ 0 \end{vmatrix} \qquad V_{T_k} = \begin{vmatrix} 0 \\ 0 \\ V_{T_k,T} \end{vmatrix}$$

the plot shows the 6 first eigenfunctions of the Q subset for IPHI

Mode designators

348.184974 ← eigenfrequency

Q 0- 1- 0

- \# of voltage nodes in segment #3
- state of coupling-circuit #2 ("–" = inverting)
- \# of voltage nodes in segment #2
- state of coupling-circuit #1 ("–" = inverting)
- \# of voltage nodes in segment #1

"Q_n" is the nickname for the accelerating mode; here "Q_n" is Q 0+0+0

TLM Properties (3/3)

First-order perturbation analysis reveals **dual bases** for parameter perturbation functions and resulting voltage perturbation functions. Example:

capacitance perturbations

$$C_1 = C_{QQ} + C_{SQ} + C_{SSTT}$$
$$C_2 = C_{QQ} - C_{TQ} - C_{SSTT}$$
$$C_3 = C_{QQ} - C_{SQ} + C_{SSTT}$$
$$C_4 = C_{QQ} + C_{TQ} - C_{SSTT}$$

$$\begin{vmatrix} \Delta C_{QQ} \\ \Delta C_{SQ} \\ \Delta C_{TQ} \end{vmatrix} = \sum_{\delta=0}^{\propto} p_{QQ_\delta} C_{Q_\delta} + \sum_{\alpha=0}^{\propto} p_{SQ_\alpha} C_{S_\alpha} + \sum_{\beta=0}^{\propto} p_{TQ_\beta} C_{T_k}$$

eigenpair perturbation with duality relations

$$\Delta\lambda_{Q_n} \;,\; \Delta V_{Q_n} = \sum_{\substack{i=0 \\ i\neq n}}^{\propto} c_{Q_i} V_{Q_i} + \sum_{j=0}^{\propto} c_{S_j} V_{S_j} + \sum_{k=0}^{\propto} c_{T_k} V_{T_k}$$

$$\Delta\lambda_{Q_n} = p_{QQ_n}$$
$$c_{Q_i}(\lambda_{Q_n} - \lambda_{Q_i}) = p_{QQ_i}$$

$$c_{S_j}(\lambda_{Q_n} - \lambda_{S_j}) = p_{SQ_j}$$

$$c_{T_k}(\lambda_{Q_n} - \lambda_{T_k}) = p_{TQ_k}$$

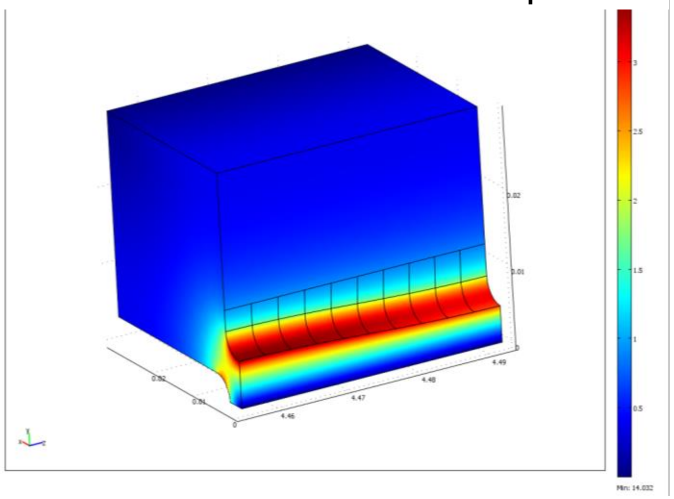
$\{ c_{Q_i}, c_{S_j}, c_{T_k} \}_{0\leq i,j,k\leq\propto}$ is the spectral analysis of ΔV_{Q_n}

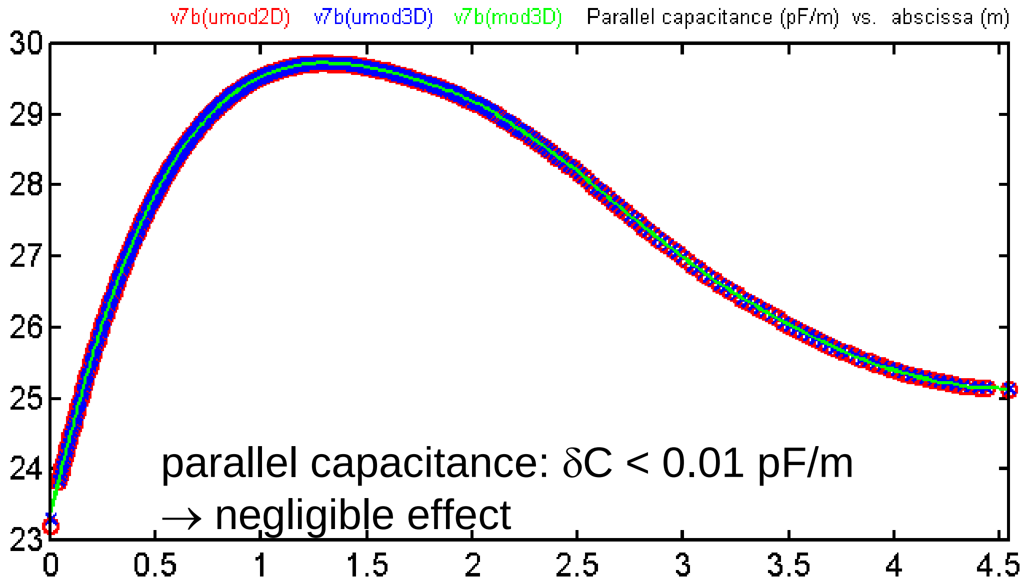
Effects of Modulations on Line Parameters

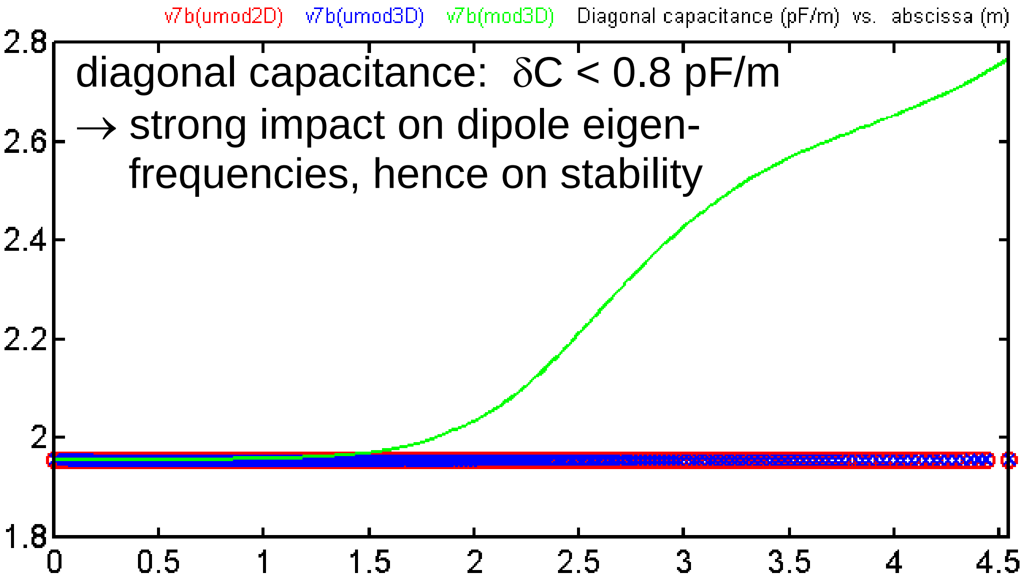
ESS RFQ 2D/3D simulations

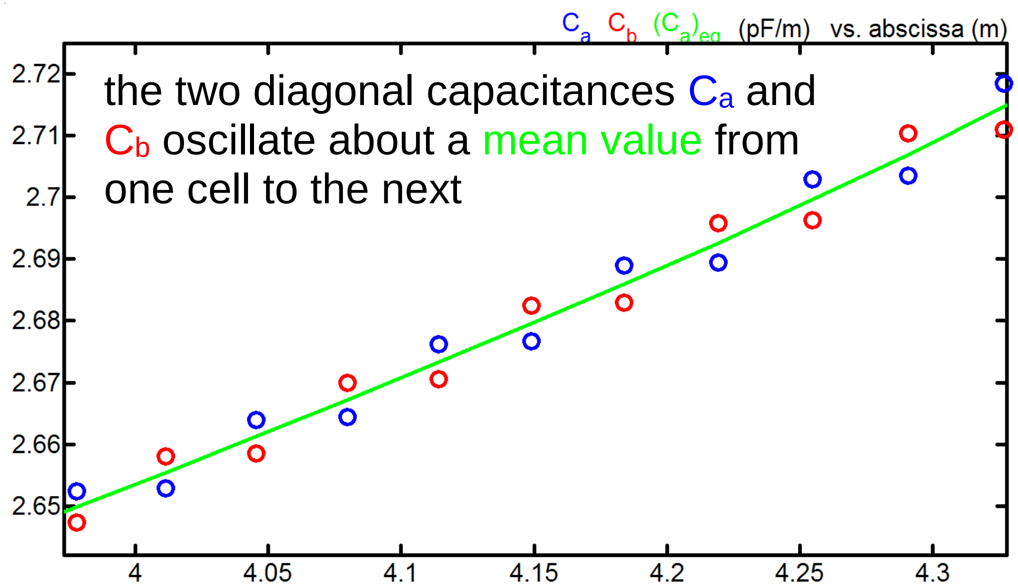
un-modulated 2D / un-modulated 2D / modulated 3D

one simulation cell= one half-period



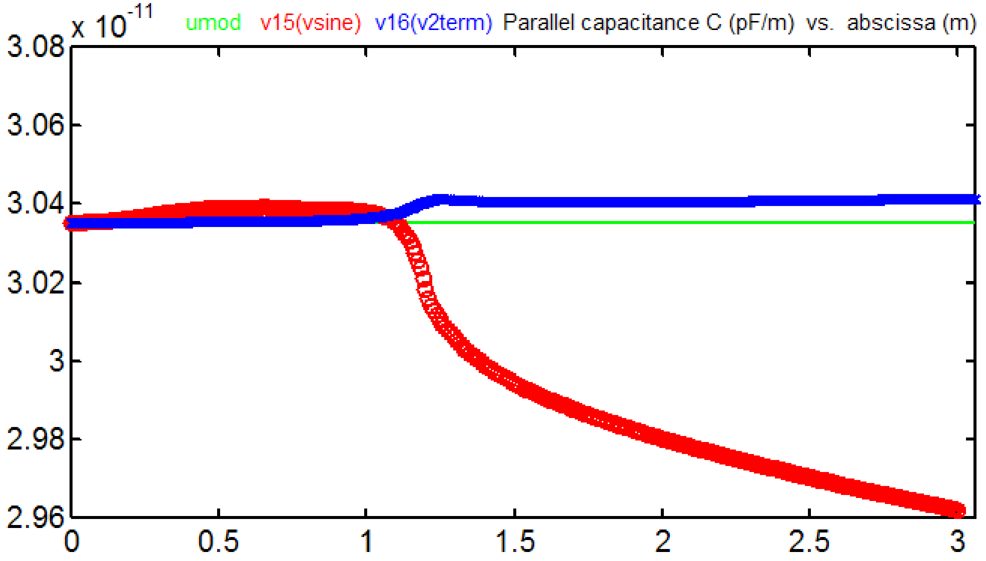


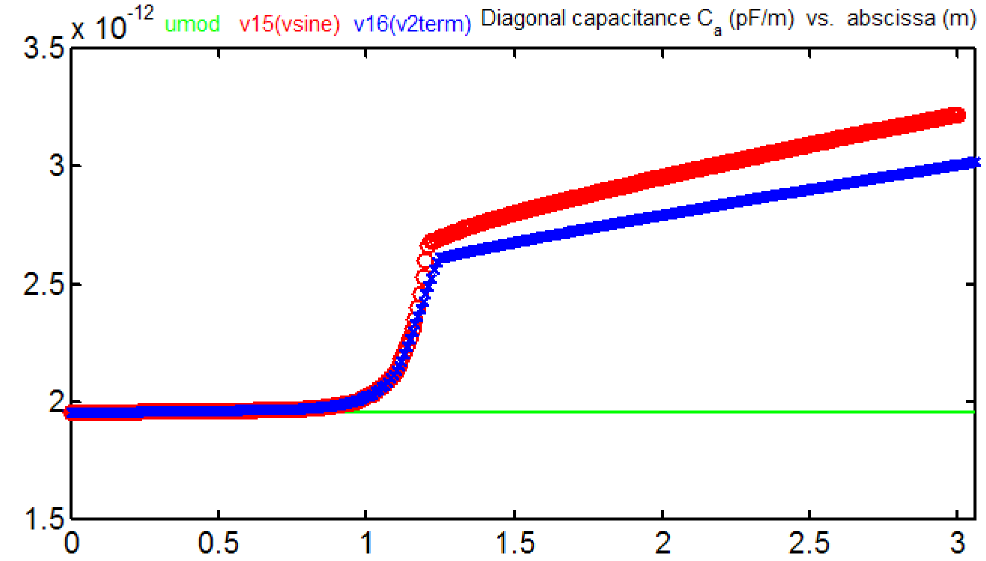




Effects of Modulation Style

LINAC4 RFQ 2D/3D simulations (Comsol)





→ un-modulated profile of LINAC4 electrodes is constant

→ 3 simulations:
– in green : un-modulated electrodes
– in red : sine modulation
– in blue : 2-term potential modulation

→ the sine modulation induces too much detuning for reasonable slug dimensions.
RFQ cross-section could not be kept constant.

2. End and Coupling Circuits Tuning

End and Coupling Circuits Tuning

End circuit s matrix (ex. in $z = a$)

$$\begin{vmatrix} \partial U_Q/\partial z \\ \partial U_S/\partial z \\ \partial U_T/\partial z \end{vmatrix} = -\begin{vmatrix} s_{QQ} & s_{QS} & s_{QT} \\ s_{SQ} & s_{SS} & s_{ST} \\ s_{TQ} & s_{TS} & s_{TT} \end{vmatrix} \begin{vmatrix} U_Q \\ U_S \\ U_T \end{vmatrix}$$

$= 0$ $= 0$

(since $U_T(z) = U_S(z) = 0$ $\forall z$ in the tuned RFQ)

$$s_{QQ} = -\frac{1}{V(a)}\frac{\partial V(a)}{\partial z}$$

$V(z)$ = specified voltage

Coupling circuit s matrix (in $z = c$)

$$\begin{vmatrix} \partial U_Q^-/\partial z \\ -\partial U_Q^+/\partial z \end{vmatrix} = \begin{vmatrix} s_e^- + s_c & -s_c \\ -s_c & s_e^+ + s_c \end{vmatrix} \begin{vmatrix} U_Q^- \\ U_Q^+ \end{vmatrix}$$

coupling coefficient $s_c = \frac{\omega^2}{\nu^2}\frac{C_c}{4C}$

$U_Q^- = U_Q^+$ in the tuned RFQ $\quad s_e^- = -s_e^+ = \frac{1}{V(c)}\frac{\partial V(c)}{\partial z}$

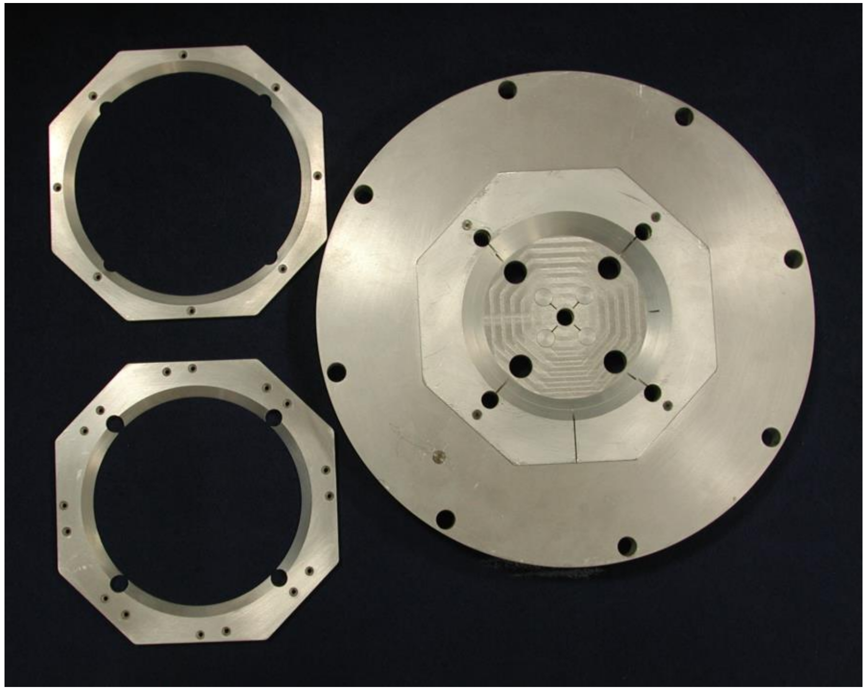
$$s_{\Sigma\Sigma} = \frac{1}{2}(s_e^- - s_e^+) = \frac{1}{V(c)}\frac{\partial V(c)}{\partial z}$$ *tuning*

$$s_{\Delta\Sigma} = -\frac{1}{2}(s_e^- + s_e^+) = 0$$ *matching*

tuning : adequate voltage slope across boundary

matching : continuous voltage across boundary

Tunable Devices for End and Coupling Circuits



adjustable thickness

IPHI input end-plate
IPHI coupling-plates #1 and #2

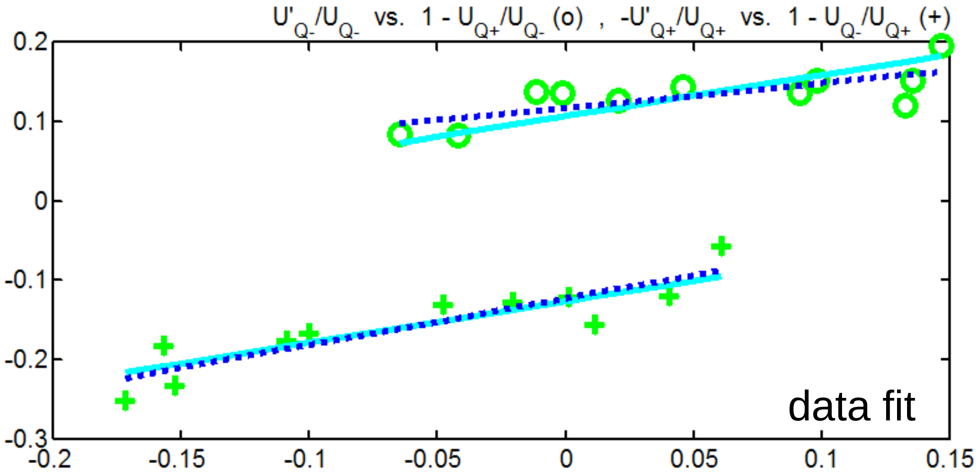
adjustable "quadrupole" rods

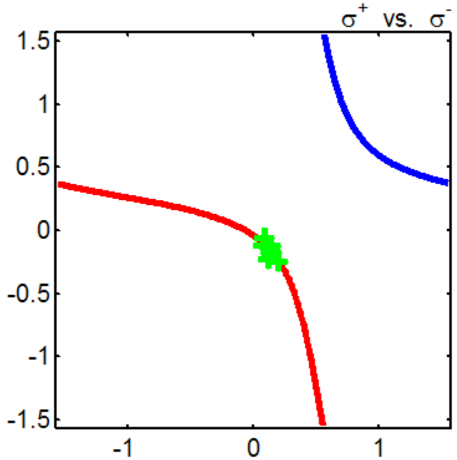
IPHI output end-plate
LINAC4 input and output plates
SPIRAL2 input and output end-plates
ESS input and output end-plates

The Excitation Set Method

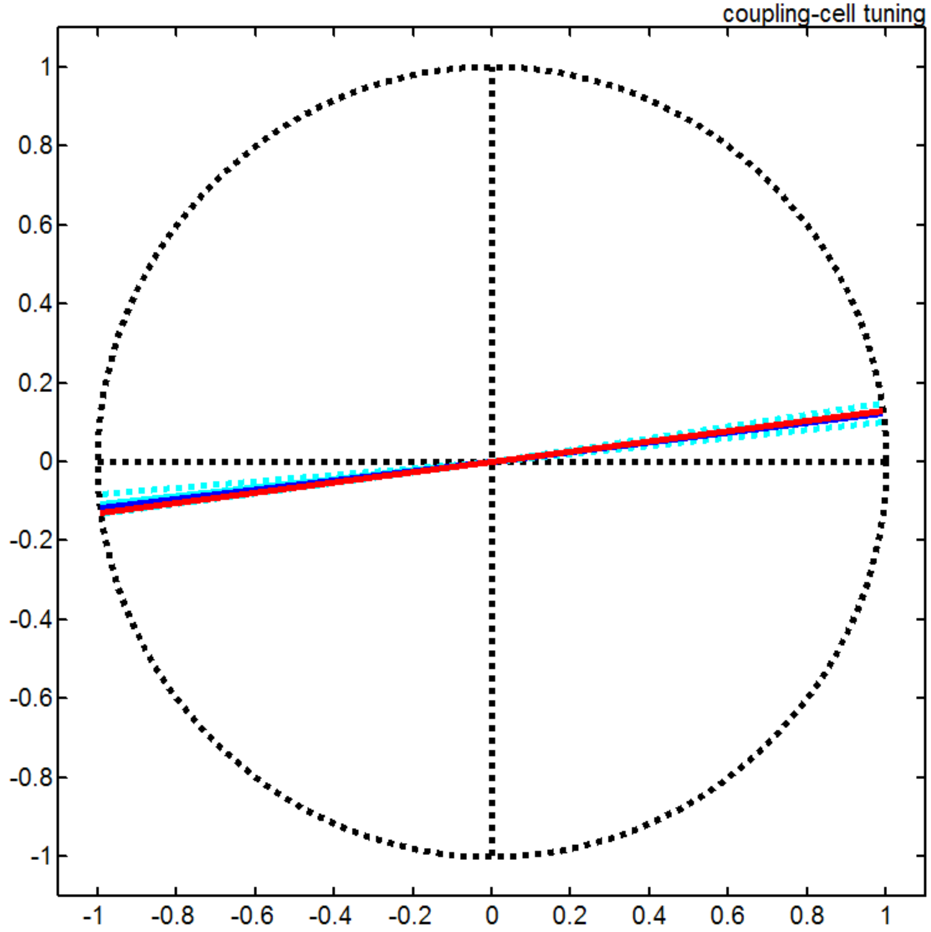
Use M linearly independent pairs $\{\partial U/\partial z, U\}$ to estimate unknown coefficients of s matrixes.
Excitations are obtained with M preset tuner positioning at some distance from boundary.
M = 5 for end circuits; M = 11 for coupling circuits (number of bead-pulls is M).

Example: IPHI coupling circuit #2





state equation: non-inverting branch in red



matching and tuning conditions

IPHI and LINAC4 Realized Boundary Conditions

legend: good / not good, don't know why / fair, know why. s parameters in m^{-1} ("V/m/V")

		expected	tuning (aluminum)	tuned (copper)
IPHI				
input end-circuit	s_{QQ}	0.0	$-5.46\ 10^{-3}$	$-3.04\ 10^{-2}$
	$\sigma(s_{QQ})$		$1.55\ 10^{-2}$	$3.01\ 10^{-2}$
coupling-circuit #1	$s_{\Sigma\Sigma}$	$+7.91\ 10^{-2}$	$+7.33\ 10^{-2}$	$+9.45\ 10^{-2}$
	$s_{\Delta\Sigma}$	0.0	$+9.29\ 10^{-3}$	$-9.59\ 10^{-2}$
	C_c	1.1 pF	0.71 pF	0.53 pF
coupling-circuit #2	$s_{\Sigma\Sigma}$	$1.30\ 10^{-1}$	$+1.07\ 10^{-1}$	$+1.20\ 10^{-1}$
	$s_{\Delta\Sigma}$	0.0	$+1.82\ 10^{-2}$	$+2.39\ 10^{-3}$
	C_c	1.1 pF	0.93 pF	0.95 pF
output end-circuit	s_{QQ}	$2.11\ 10^{-2}$	n/a	$+2.85\ 10^{-2}$
	$\sigma(s_{QQ})$		n/a	$1.67\ 10^{-2}$
LINAC4				
input end-circuit	s_{QQ}	0.0	$+2.78\ 10^{-2}$	$+6.26\ 10^{-2}$
	$\sigma(s_{QQ})$		$7.00\ 10^{-2}$	$2.41\ 10^{-2}$
output end-circuit	s_{QQ}	0.0	n/a	$-7.67\ 10^{-2}$
	$\sigma(s_{QQ})$		n/a	$2.97\ 10^{-2}$

3. Stability Design, Tuning and Measurement

Stability Analysis

"stability" w.r.t. undesired perturbations under operation

impulse error function

QQ impulse error function

the voltage relative perturbation vs. z → $\frac{\Delta V_{Qn,Q}(z)}{V_{Qn,Q}(z)} = h_{Qn,Q}(z,z_0)\frac{\Delta c_{QQ}}{C(z_0)}$ ← a Dirac-like QQ perturbation with mass $\Delta c_{QQ}/C$ located in $z = z_0$

idem for SQ and TQ functions:

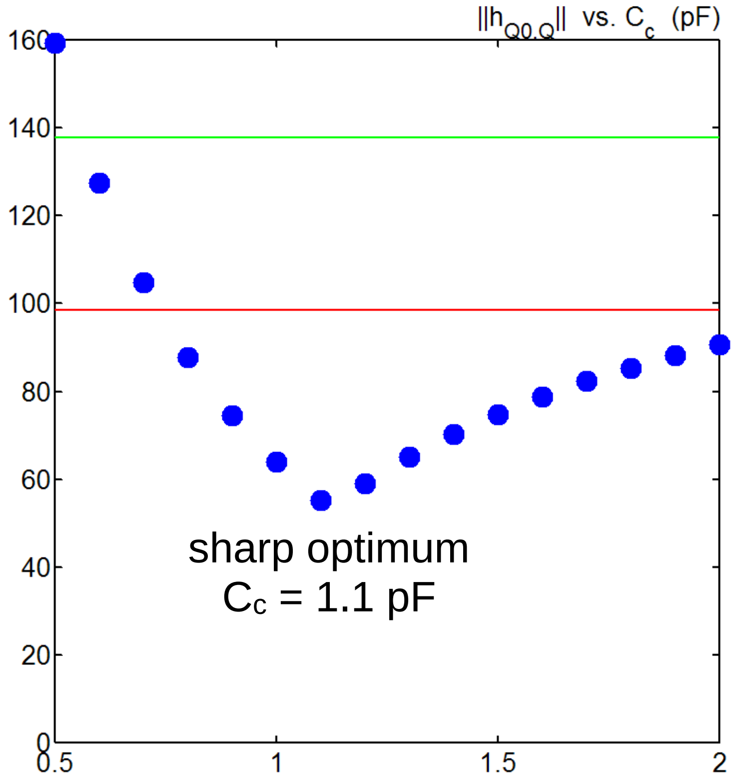
$$\frac{\Delta V_{Qn,S}(z)}{V_{Qn,Q}(z)} = h_{Qn,S}(z,z_0)\frac{\Delta c_{SQ}}{C(z_0)} \qquad \frac{\Delta V_{Qn,T}(z)}{V_{Qn,Q}(z)} = h_{Qn,T}(z,z_0)\frac{\Delta c_{TQ}}{C(z_0)}$$

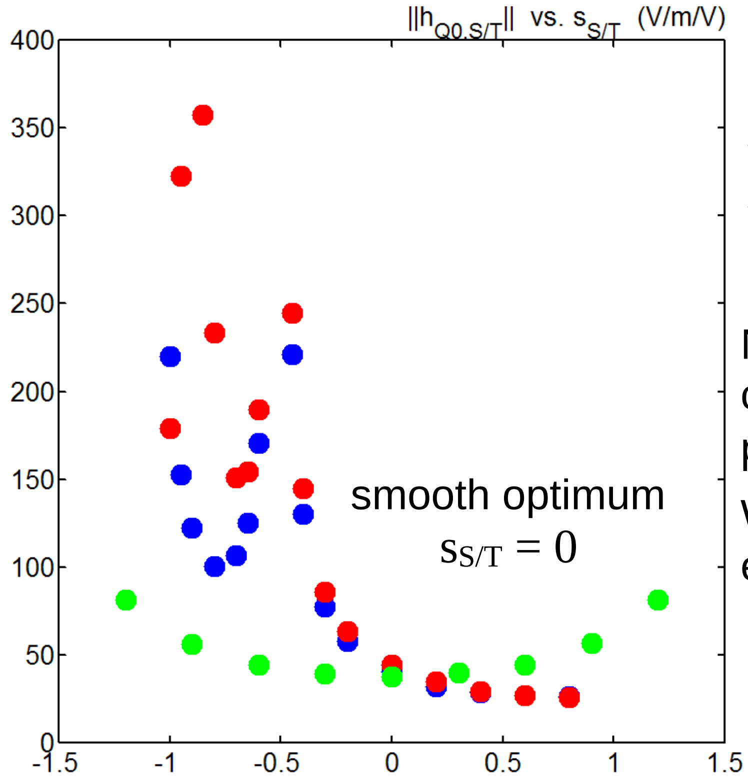
compare RFQ designs with the noms $\|h_{Qn,Q}\| := \sup_{z_0\in\Omega}\ \sup_{z\in\Omega} |h_{Qn,Q}(z,z_0)|$, $\|h_{Qn,S}\|$, $\|h_{Qn,T}\|$

these functions depend on $\frac{1}{\lambda_{Q_n}-\lambda_{Q_i}}, \frac{1}{\lambda_{Q_n}-\lambda_{S_j}}, \frac{1}{\lambda_{Q_n}-\lambda_{T_k}}$ i.e. on quadratic differences $f_{Q_n}^2 - f_{Q_i}^2$, $f_{Q_n}^2 - f_{S_j}^2$, $f_{Q_n}^2 - f_{T_k}^2$, and are infinite when an eigenmode coincides with Q_n.

IPHI Stability

legend: unsegmented / segmented, specification / segmented, realized





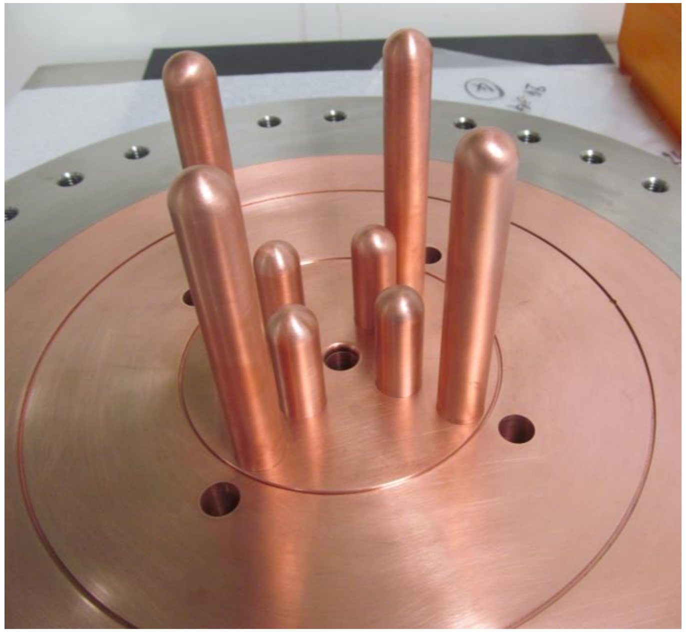
$s_{SS}, s_{TT}, s_{Se}^{-}, s_{Se}^{+}, s_{Te}^{-}, s_{Te}^{+} \approx -1$ without dipole rods, and ≈ 0 with dipole rods

Note that a short rod ($\ell < \lambda_0/2$) is capacitive, hence its admittance is positive, and it may only increase s.

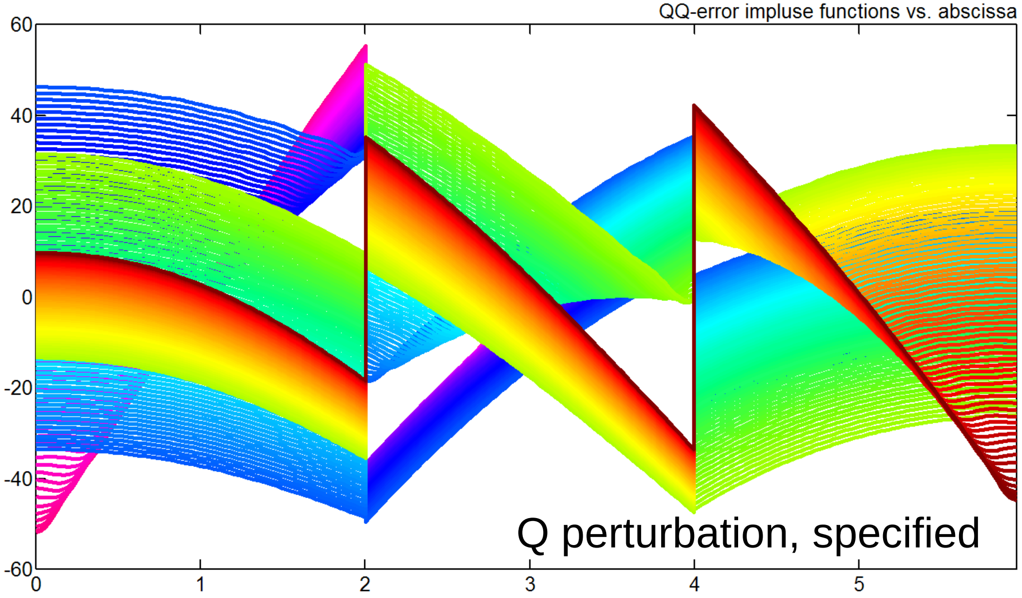
When $\ell \approx \lambda_0/2$, $s = \propto$, and the RFQ end is a short-circuit.

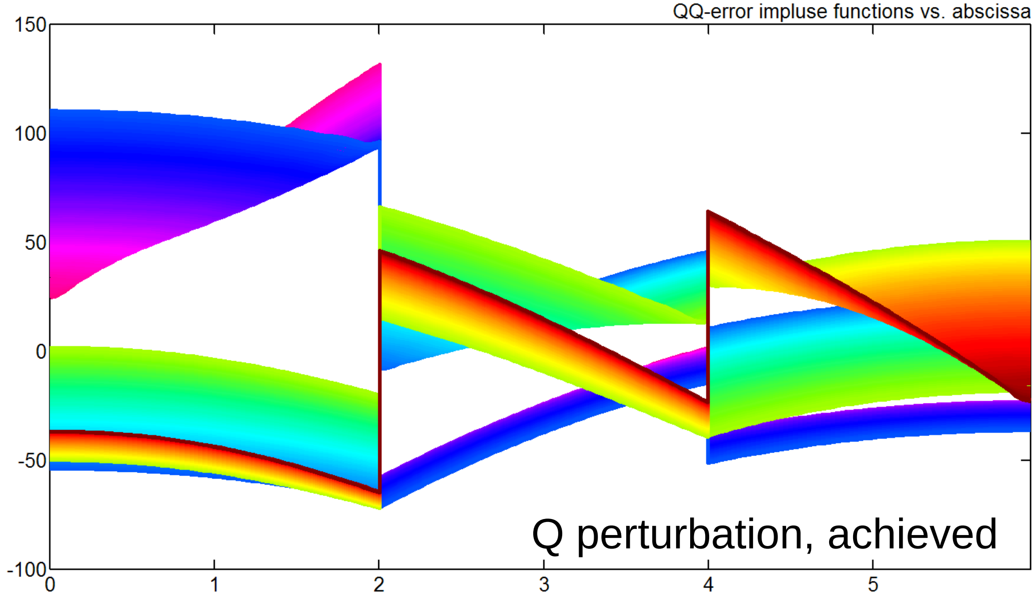
mode des.	specification	prior to slug tuning	after slug tuning
Q 0–1–0	348.18 [–42.0]	349.55 [–25.1]	351.25 [–24.5]
Q 0+0+0 "Q$_n$"	350.71 [0.00]	350.45 [0.0]	352.10 [0.0]
Q 1–1–1	353.69 [+47.8]	354.65 [+54.4]	356.40 [+55.2]
D 1+1+1	347.67 [–46.1]	348.10 [–40.5]	349.30 [–44.3]
Q 0+0+0 "Q$_n$"	350.71 [0.0]	350.45 [0.0]	352.10 [0.0]
D 2–2–2	363.16 [+94.3]	362.60 [+93.1]	364.30 [+93.5]

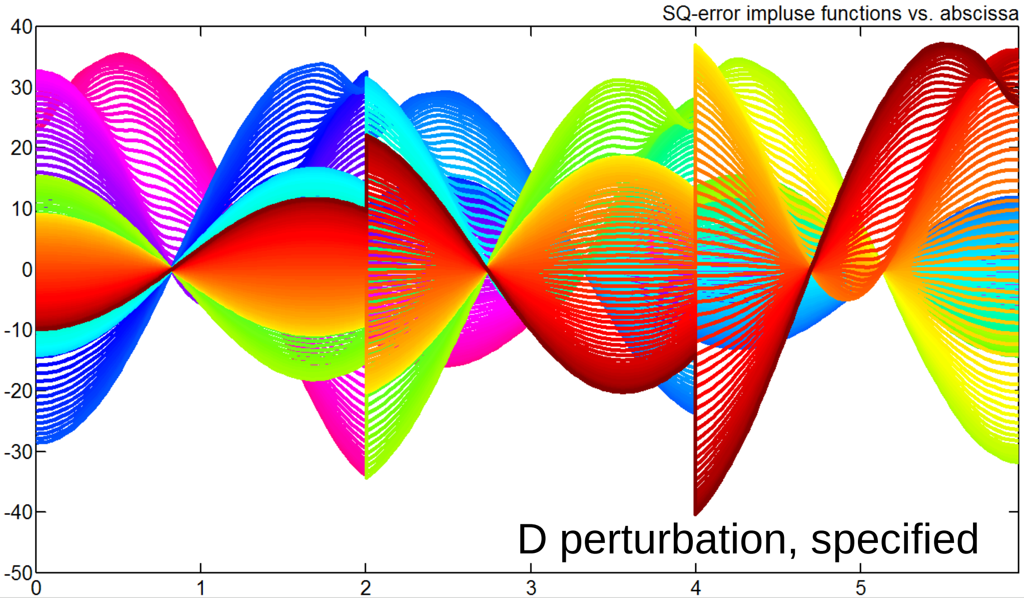
Eigenfrequencies and quadratic frequency separations (QFS) in MHz.

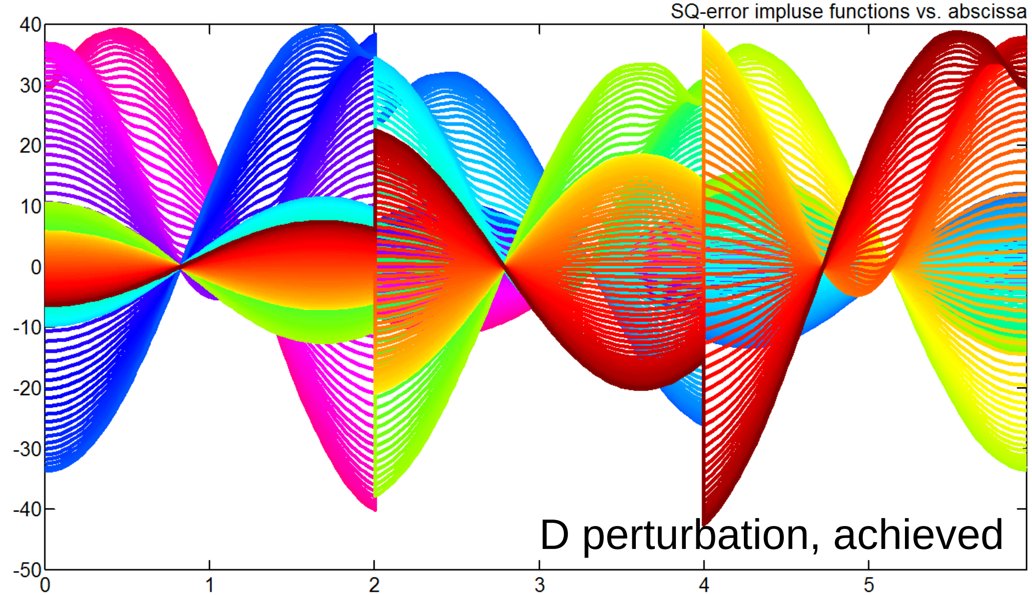


IPHI Impulse Error Functions



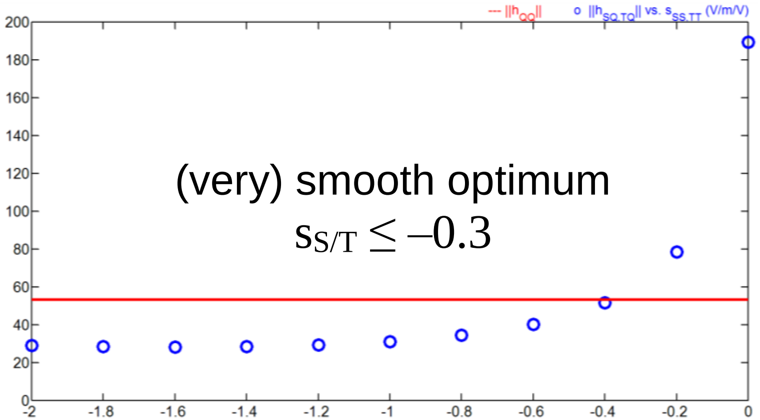


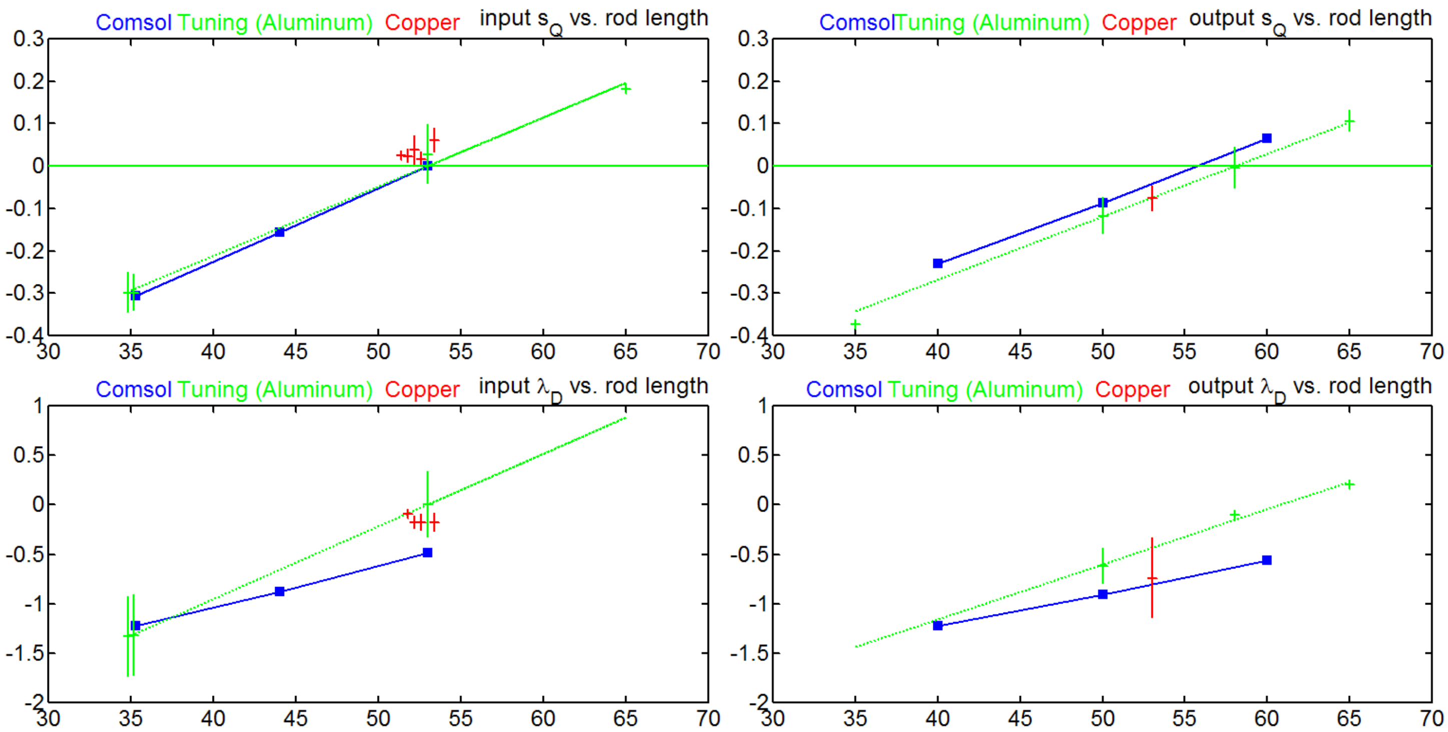




LINAC4 Stability

– measured s parameter in dipole subspace not in agreement with calculated value, but in agreement with measured spectra
– rod length is chosen smaller than optimum for $s_{QQ} = 0$ to save dipole stability



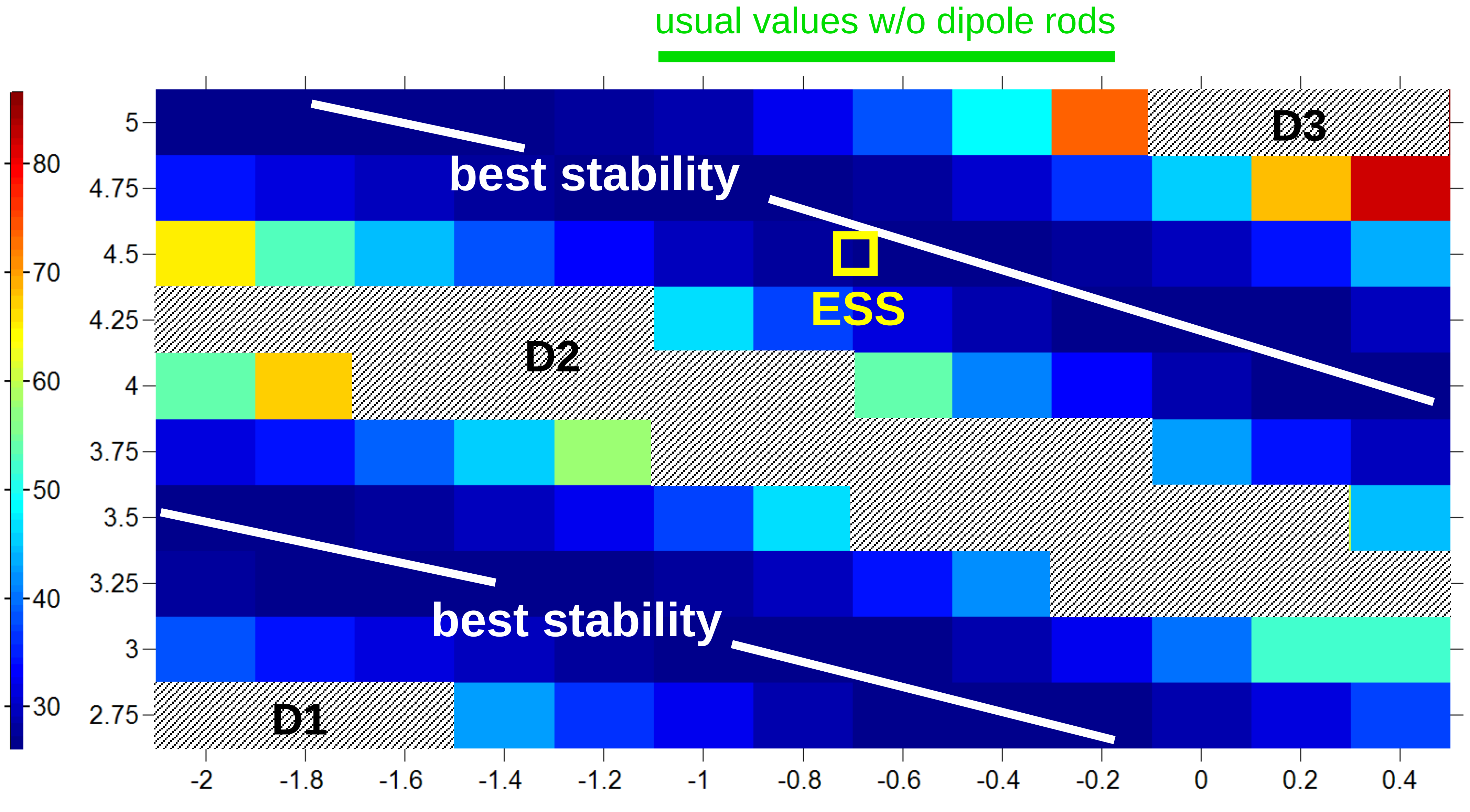


Rods (mm)	**53.0 / 55.7**	**53.0 / 53.0**		**53.0 / 53.0**
	specification	**prior to slug tuning**		**after slug tuning**
	Comsol + TLM	**measured**	**TLM (measured s)**	**measured**
Q 0 "Q_n"	345.32 [0.00]	345.50 [0.0]	345.33 [0.0]	352.13 [0.0]
Q 1	348.82 [+49.3]	348.69 [+47.0]	348.84 [+49.3]	355.31 [+47.5]
D 1	338.45 [–68.5]	338.50 [–69.2]	338.06 [–70.5]	344.63 [–72.3]
Q 0 "Q_n"	345.32 [0.0]	345.50 [0.0]	345.33 [0.0]	352.13 [0.0]
D 2	348.42 [+46.4]	347.88 [+40.6]	347.96 [+42.7]	353.50 [+31.2]

ESS Stability Design

$\| h_{Qn,S/T} \|$ vs. end boundary condition parameter $s_{S/T}$ and RFQ length ℓ

optimal RFQ length $\ell^* = \sqrt{\kappa^2 + \kappa + \frac{1}{2}\sqrt{(1+r)/r}}\,\frac{\pi\nu}{\omega_{Q_0}}$ $\quad s_{S/T} = 0, \quad \kappa \in \mathbb{N}$



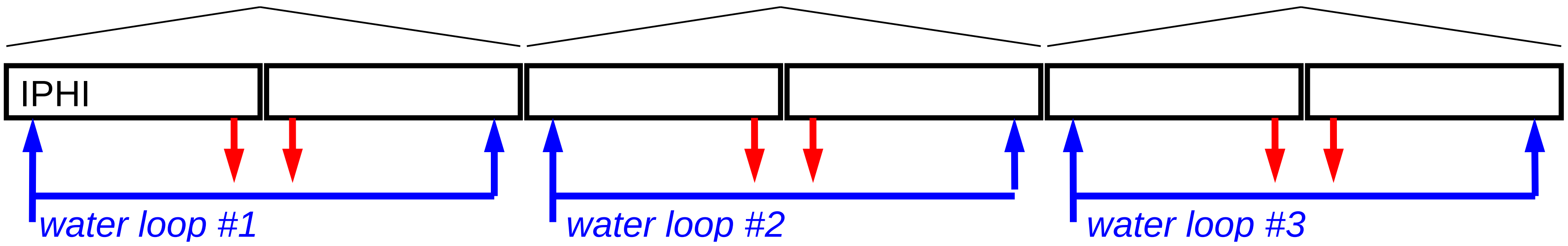
Sensitivity to Perturbations under Operation

CW linacs : deformations due to RF heating / water cooling combination

low duty cycle linacs : thermal expansions due to water temperature variations

→ spectral contents of perturbation is important

→ in general alternating water flow direction from one module to the next is better



apply perturbation – capacitance basis function with adequate spectral index

– peak value of relative perturbation = 0.001 arb.

calculate peak value of resulting voltage perturbation

	IPHI	LINAC4	SPIRAL2	ESS
number of modules	6	3	5	5
sup $\Delta V_{Qn,Q} / V_{Qn,Q}$	$5.34\ 10^{-3}$	$5.53\ 10^{-3}$	$3.36\ 10^{-4}$	$4.48\ 10^{-3}$
sup $\Delta V_{Qn,S/T} / V_{Qn,Q}$	$5.22\ 10^{-4}$	$7.88\ 10^{-3}$	$3.18\ 10^{-4}$	$5.84\ 10^{-3}$

Measured Voltage Stability of LINAC4 (1/2)

Voltage monitoring:

- pickup loops inserted in 16 slug tuners (4 quadrants in 4 cross-sections)
- calibration: low RF power, nominal water temperatures, reference = bead-pull values
- voltage reconstruction: TLM and sampling therory

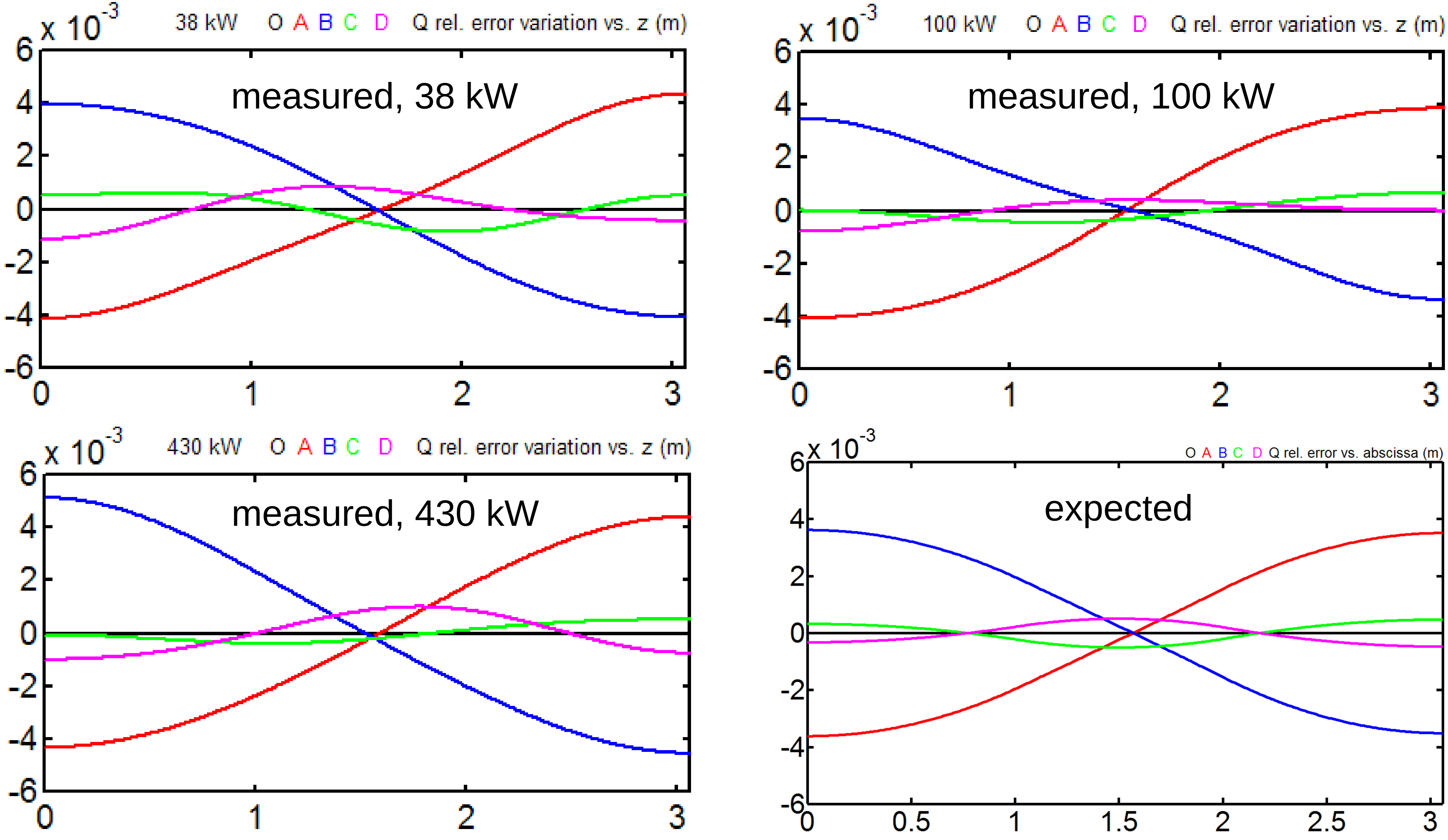
Temperature variations:

- water temperatures in the 3 RFQ modules are controled independently
- 5 temperature distributions:

O	26.0	–	26.0	–	26.0	(nominal)
A	25.5	–	26.0	–	26.5	
B	26.5	–	26.0	–	25.5	
C	26.5	–	26.0	–	26.5	
D	25.5	–	26.0	–	25.5	

- 3 RF powers 38 kW, 100 kW, 430 kW (PD = 250 μs, PRI = 1.2 s)

Measured Voltage Stability of LINAC4 (2/2)



4. Voltage and Frequency Tuning

The Voltage & Frequency Tuning Loop (1/3)

Idea: apply 1st-order perturbation theory to TLM to build dual bases:

– a discrete basis of tuner command functions

(tuner position or equivalently inductance perturbation)

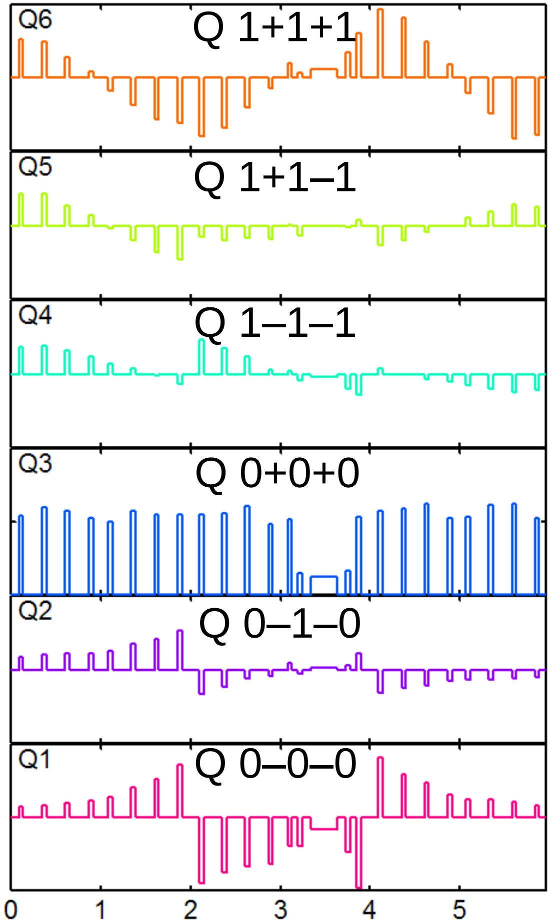
– a truncated basis of voltage eigenfunctions

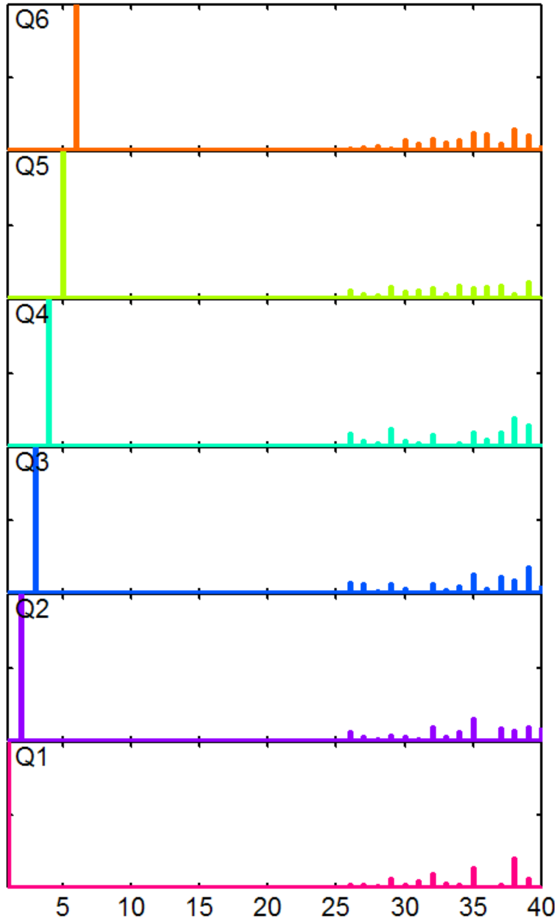
$\rightarrow$ both are calculated with given boundary conditions, which should be tuned first

IPHI's 6 first tuner command functions in Q subset.

dim. = 25 (tuning devices in 25 cross-sections)

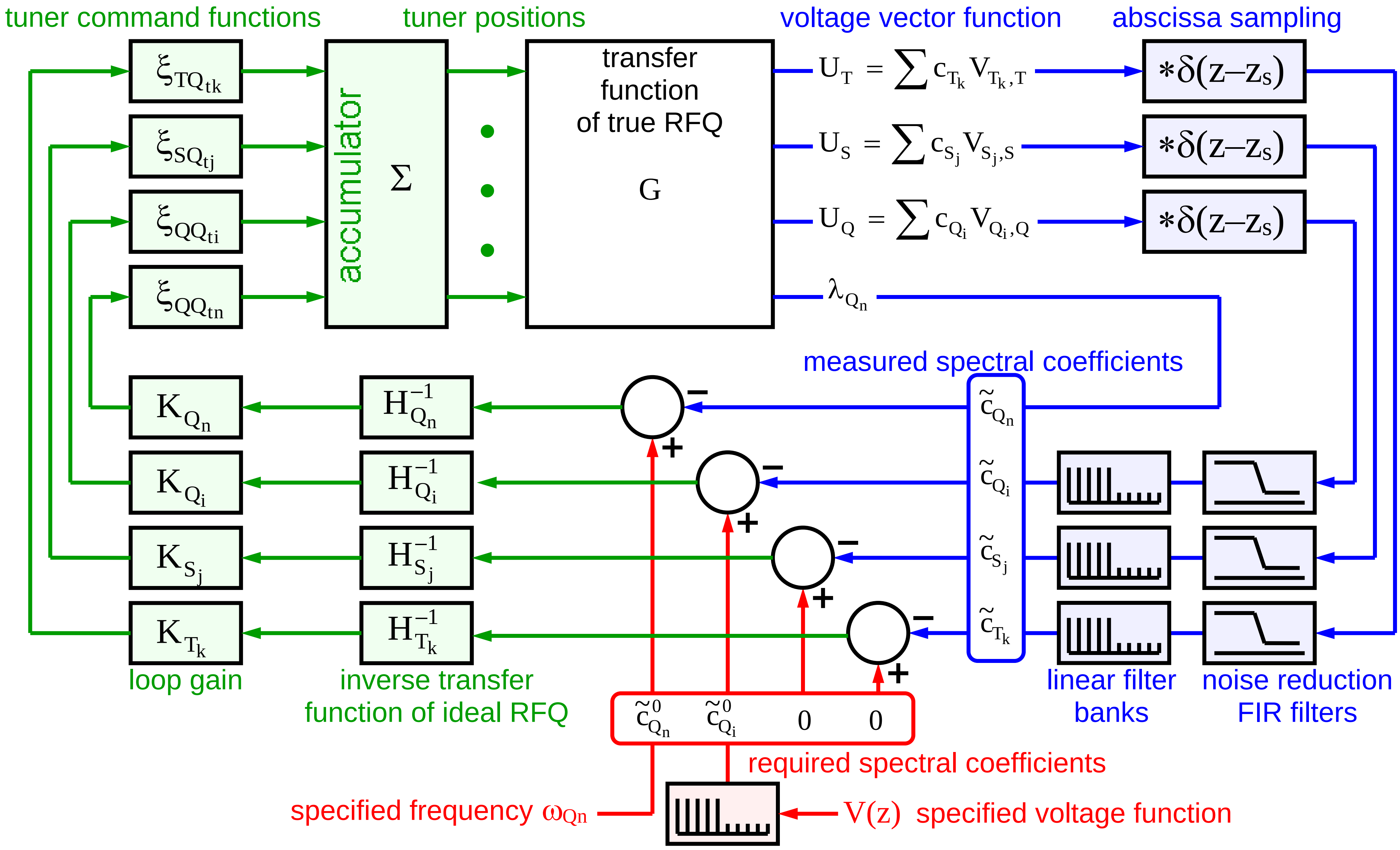
"Q_n" : frequency tuning $\rightarrow$





spectral coefficients of voltage perturbation resulting from each command function

The Voltage & Frequency Tuning Loop (2/3)

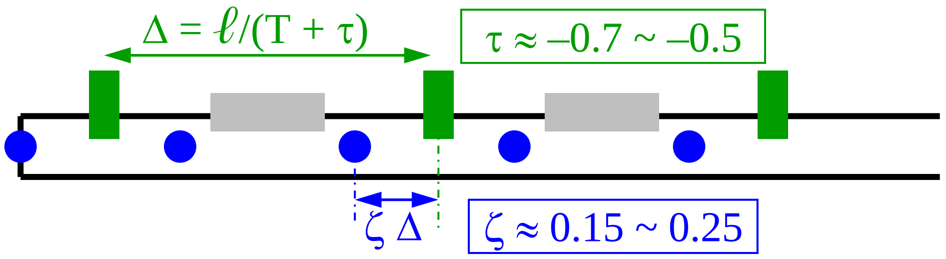


The Voltage & Frequency Tuning Loop (3/3)

working conditions

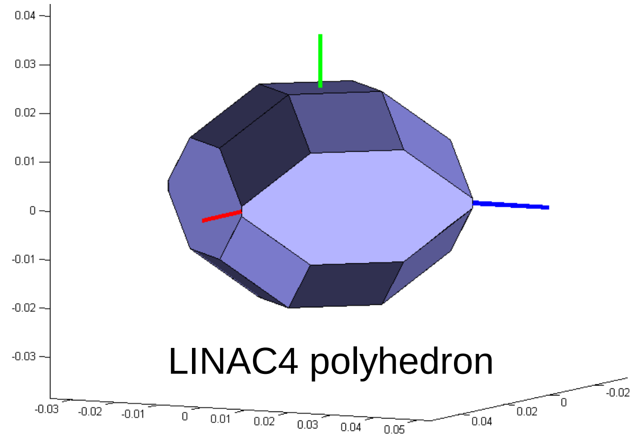
Voltage sampling:

- magnetic field samples (bead-pull) should reside far enough from local perturbations
- tune vacuum ports in electrically neutral position prior to braze if possible (Linac4)
- full-rank sampling
- output of filter banks free from aliasing



Inductance sampling:

- full-rank sampling (include RF ports in tuning devices set)



LINAC4 polyhedron

Tuner efficiency:

- use 3D simulation to determine individual tuner slope ∂L/∂h for TLM
- derive capacitance vs. intervane gap fcn. from simulations
- transform mechanical tolerance into capacitance error polyhedron
- use TLM + linear programming (Danzig) to determine worst tuning case

Tuning loop:

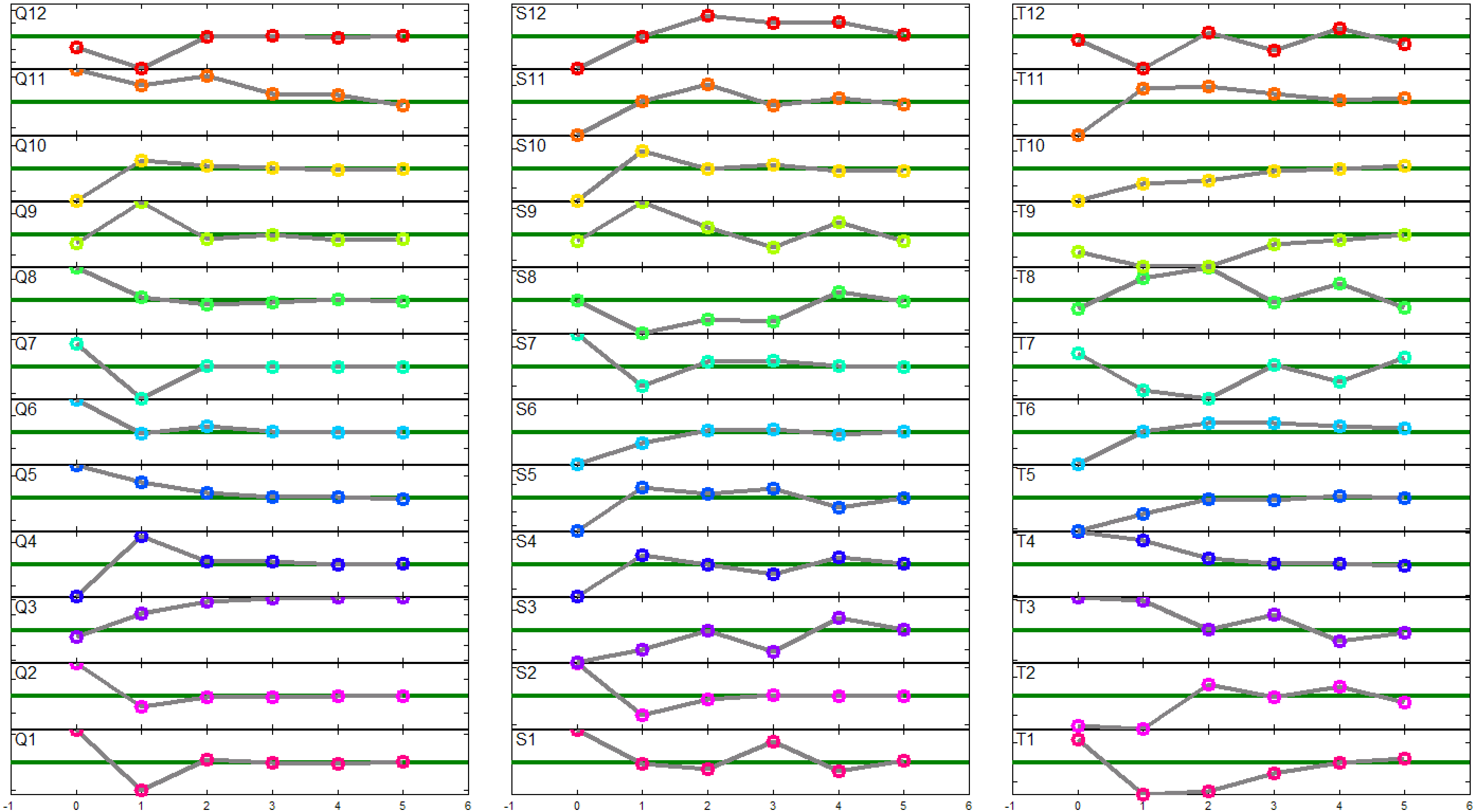
- unbiased
- equivalent to fixed-point iteration of the operator $A = I - G\,K\,H^{-1}$ (with all the convergence properties of fixed-point iterations!)
- converges iff A is a contraction, here satisfied iff eigenmodes are identically sorted for the ideal and the true RFQs according to eigenvalue order
- convergence is monotonic if A is diagonal, but may be non-monotonic otherwise

IPHI and LINAC4 Tuning

IPHI			
voltage peak relative errors (%):	**Q**	**S**	**T**
dummy RF ports, un-tuned	90	17.6	14.5
adjustable slugs, RF ports, tuned	0.78	0.28	0.63
copper slugs	3.97	1.32	2.07
tuner positions (mm):			
specified		+1.0 / +19.0	
specified, with safety margin		–5.0 / +25.0	
tuned RFQ		–1.7 / +12.5	
LINAC4			
voltage peak relative errors (%):	**Q**	**S**	**T**
dummy RF port, un-tuned	5.55	5.53	7.19
adjustable slugs, RF port, tuned	0.70	1.48	3.07
copper slugs	0.63	3.45	2.29
tuner positions (mm):			
specified		–4.0 / +30.0	
tuned RFQ		+9.0 / +12.1	

IPHI Voltage Tuning

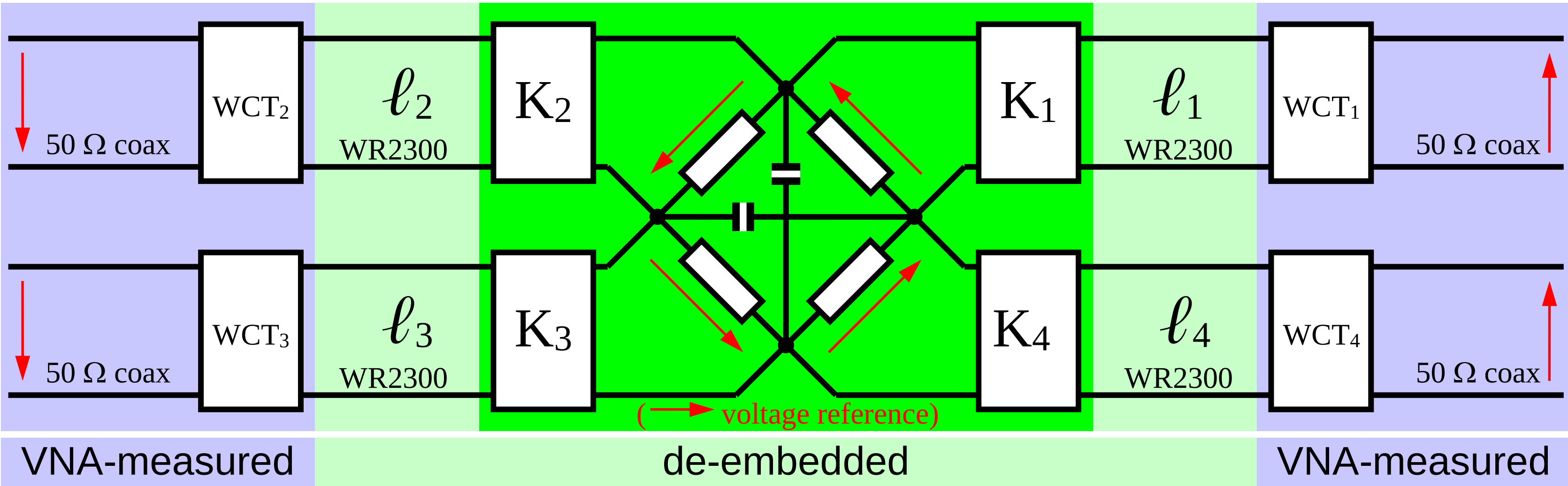
spectral coefficients vs. tuning step index in initial pre-tuning sequence

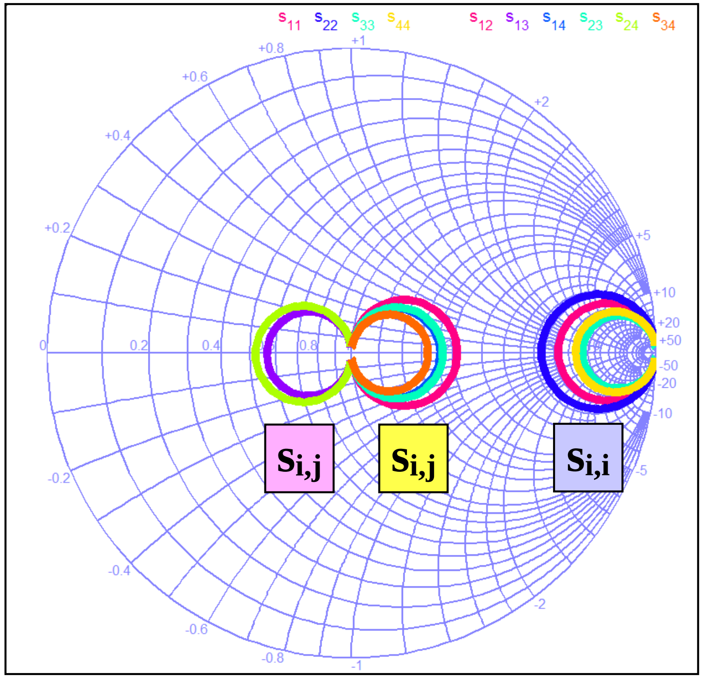


5. RF Power Coupling

The Structure of the 4 × 4 Scattering Matrix

in the case of ideal, quaternary-symmetric RFQ



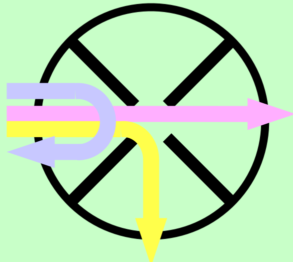


$$S = \begin{vmatrix} S_{1,1} & S_{1,2} & S_{1,3} & S_{1,4} \\ S_{1,2} & S_{2,2} & S_{2,3} & S_{2,4} \\ S_{1,3} & S_{2,3} & S_{3,3} & S_{3,4} \\ S_{1,4} & S_{2,4} & S_{3,4} & S_{4,4} \end{vmatrix}$$

$$s_{i,j}(\omega) \approx \frac{\sqrt{\beta_i \beta_j}}{1+\beta}\left(1+e^{j\alpha(\omega)}\right)\zeta_{i,j}(\omega) \qquad (\beta_i \sim 1/K_i^2)$$

$$s_{i,j}(\omega) \approx -\left(\frac{\sqrt{\beta_i \beta_j}}{1+\beta}\left(1+e^{j\alpha(\omega)}\right)+j\sqrt{\beta_i \beta_j}\,H(\omega)\right)\zeta_{i,j}(\omega)$$

$$s_{i,j}(\omega) \approx \left(1-\frac{\beta_i}{1+\beta}\left(1+e^{j\alpha(\omega)}\right)+j\beta_i H(\omega)\right)\zeta_{i,i}(\omega)$$



circle

imaginary offset

propagation phasor (circular projection)

A Few Essential S-matrix Properties

1. quarter-wave transformers my be represented by K-inverters with excellent accuracy in the complex plane (10^{-8} in simulations)

2. S-parameters of asymmetric RFQ may be represented by S-parameters of quaternary-symmetric RFQ with very small errors in the complex plane ($10^{-4} \sim 10^{-3}$ in measurements, even smaller in simulations)
   $\rightarrow$ electrical asymmetries are non-observable in standard VNA measurements

3. Q_0, ω_0 and total coupling coefficient are correctly estimated, but partial coupling coefficients have to be corrected for voltage asymmetries (derived from bead-pull measurements)

$$\beta_i \rightarrow \beta_i \left(\frac{u_i^2}{\beta} \sum_{j=1}^{4} \frac{\beta_j}{u_j^2} \right)^{-1}$$

4. multiport matching: total power reflection coefficient is $\Gamma^2 = (a^* S^* S a)/(a^* a)$: the 4-port circuit is matched when the excitation vector a is an eigen-vector a_1 corresponding to the smallest eigenvalue λ_1 of $S^* S$.
   $\rightarrow a_1$ and $\lambda_1(\omega)$ also give estimates of Q_0, ω_0, β and β_i's, without reference to the matrix structure

The IPHI 4-Port Scattering Matrix

under vacuum

	ω_0	Q_0	β_1	β_2	β_3	β_4	β
matrix reconstruction	352.1421	6875	0.2679	0.2795	0.3123	0.2782	1.1379
with correction			*0.2693*	*0.2837*	*0.3107*	*0.2741*	
multiport matching	352.1422	6786	0.2797	0.2979	0.3218	0.2988	1.1982

S-matrix reconstruction errors

Transmission to adjacent quadrants $(i,j) \in \{ (1,2)\ (1,4)\ (2,3)\ (3,4) \}$:

S-parameter reconstruction error $|\mathrm{Re}\,\Delta s_{i,j}|,\ |\mathrm{Re}\,\Delta s_{i,j}| < 2\ 10^{-3}$

polar angle error $|\alpha_{i,j} - \alpha_0| < 0.8°$

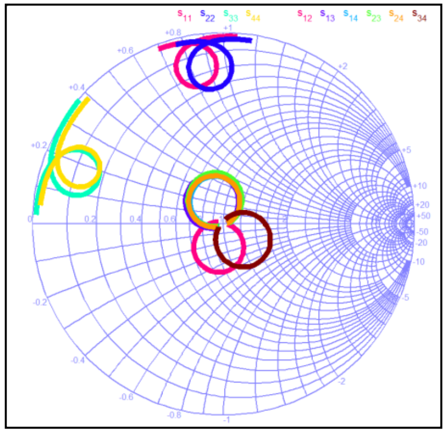
phasor closure error $|\arg(\zeta_{1,4}\zeta_{2,3}/\zeta_{1,2}\zeta_{3,4})| < 0.8°$

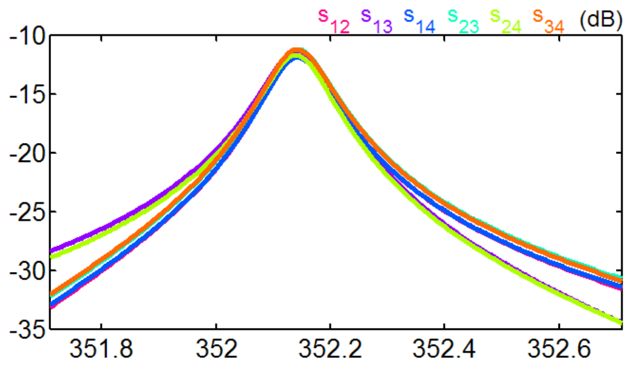
Transmission to opposite quadrant $(i,j) \in \{ (1,3)\ (2,4) \}$:

S-parameter reconstruction error $|\mathrm{Re}\,\Delta s_{i,j}|,\ |\mathrm{Re}\,\Delta s_{i,j}| < 2\ 10^{-3}$

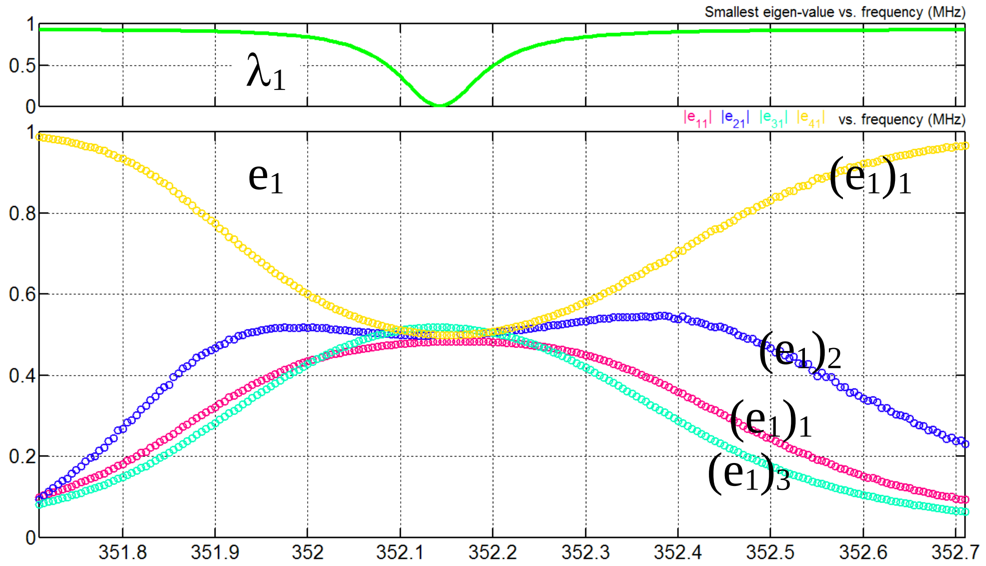
offset function $|H_{i,j} - H_0| < 2\ 10^{-3}$

phasor closure error $|\arg(\zeta_{1,3}\zeta_{2,4}/\zeta_{1,2}\zeta_{3,4})| < 3.2°$





multiport matching



Estimated power budget

RFQ = 1.17 to 1.18 MW Beam = 0.3 MW

ideal β = 1.254 to 1.257

estimated Γ = –26 dB (reconstructed matrix)

= –32 dB (multiport matching)

Final Comments

– the TLM creates accurate and invertible bridges between 3D simulations, electromagnetic specifications and measurable/observable quantities

– IPHI and Linac4 are accurately tuned

– thermal stability of Linac4 is experimentally demonstrated to be in agreement with design

– the sophistication of the electromagnetic perturbation analysis deserves an improvement of the way mechanical tolerances are specified

Thank you for attention !