Tuning of Traveling-Wave Structures

Jiaru Shi, CERN
May 4, 2010

Acknowledgement

- Contributor
  - Alexej Grudiev
  - Walter Wuensch
  - Andrey Olyunin
  - Serge Lebet
  - Juwen Wang
  - ……

Outline

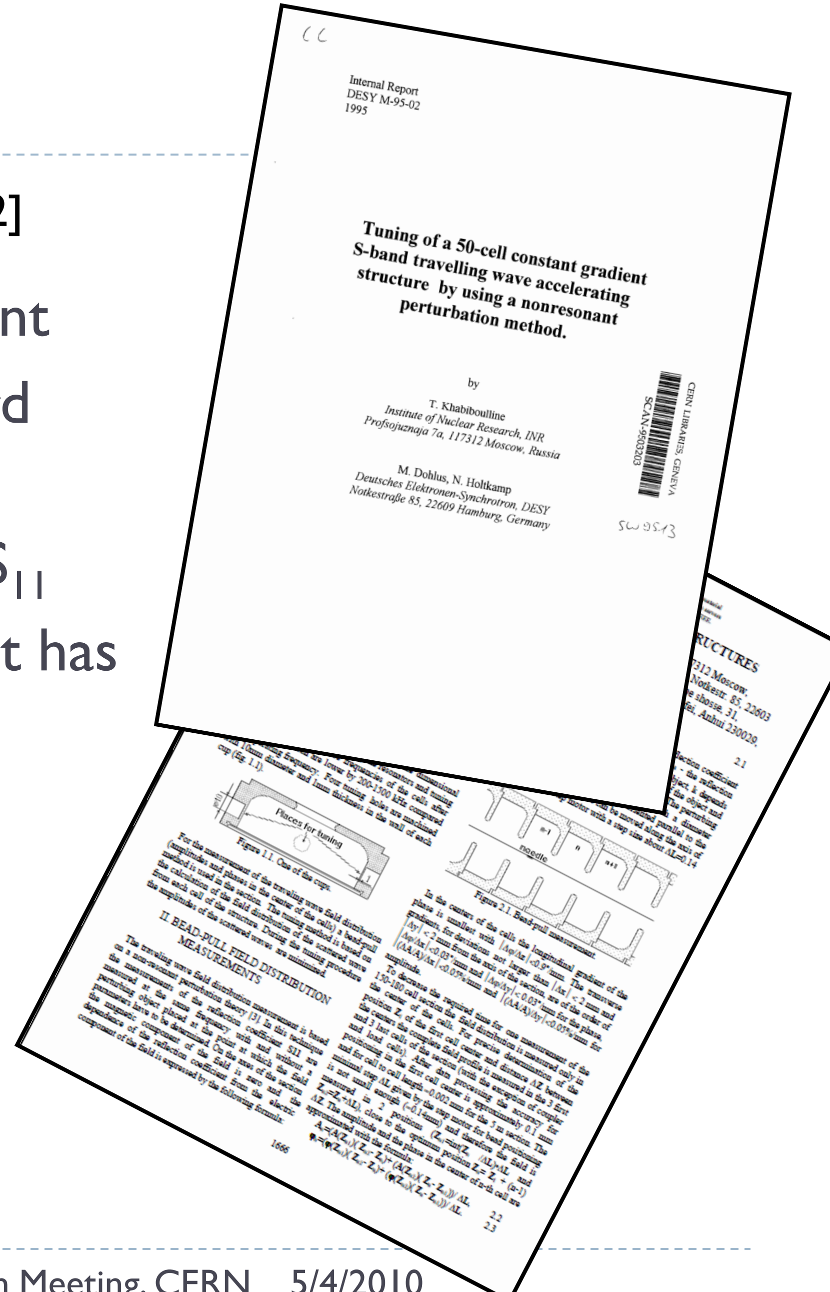
- General explanation of the method
- Tuning experiences at CERN
  - TD24
  - T18

Introduction

- Phase velocity = beam velocity
- Phase advance per cell ~ frequency
- Matching cell
  - Output matching cell→ standing-wave
- History
  - Plunger
    - Each individual cell
    - Matching the coupler
    - Iris contamination (Be careful for high gradient!!)
- Where are we?
  - Estimation of fabrication error 2~3μm?
  - 1μm of radius → 1MHz → 1 phase error / cell or 0.02 (-34dB) reflection from matching (for X-band, v_g=0.01*c*, 120),

Introduction

- The Paper of T. Khabiboulline[1,2]
  - ☺ Tuning by bead-pull measurement
  - ☺ Calculate forward and backward wave of each cell
  - 😐? Correction while monitoring S_{11}
  - ?? Output cell (the paper assume it has been tuned)
  - ?? The reflection ~ the frequency detuning


Internal Report
DESY M-95-02
1995

Tuning of a 50-cell constant gradient S-band travelling wave accelerating structure by using a nonresonant perturbation method.

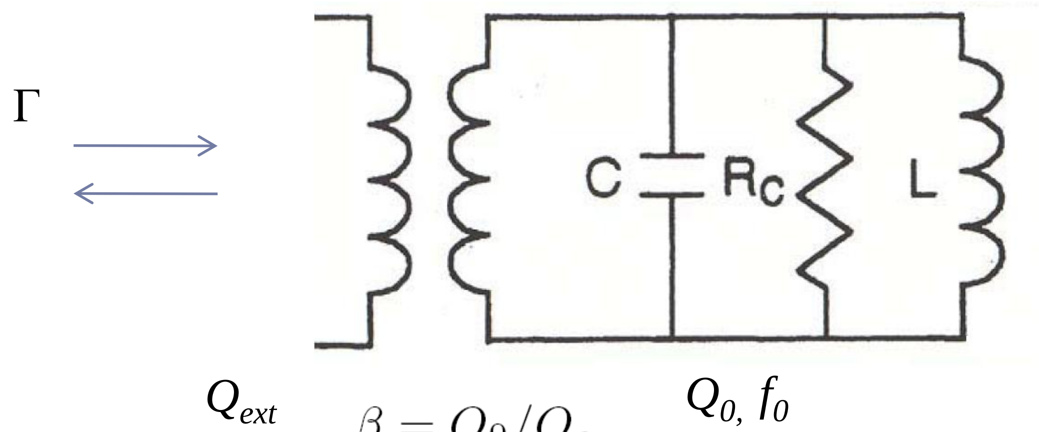
by

T. Khabiboulline
Institute of Nuclear Research, INR
Profsojuznaja 7a, 117312 Moscow, Russia

M. Dohlus, N. Holtkamp
Deutsches Elektronen-Synchrotron, DESY
Notkestraße 85, 22609 Hamburg, Germany

[1] DESY M-95-02, 1995
[2] PAC95, P1666

Reflection due to Frequency Detuning



$\beta = Q_0/Q_e$

$$\Gamma = \frac{(\beta-1)(\beta+1) - Q_0^2(\Delta F)^2}{(\beta+1)^2 + Q_0^2(\Delta F)^2} - j\frac{2\beta Q_0 \Delta F}{(\beta+1)^2 + Q_0^2(\Delta F)^2}$$

$$\Delta F = \frac{f}{f_0} - \frac{f_0}{f}$$

$\Delta F = -2\Delta f_0/f_0$ if $\Delta f_0 << f_0$

Reflection due to Frequency Detuning

- Adding both the wall-loss and the power flow to the next cell: the equivalent Q0

$$Q_0' = \frac{\omega U}{P_{\mathrm{w}} + P_{\mathrm{f}}} \approx \frac{\omega U}{P_{\mathrm{f}}} = \frac{\omega W D}{W v_g} = \frac{c\varphi}{v_g}$$

Note: *W*: stored energy per unit length (energy density)

$$P_{\mathrm{f}} = W v_g$$

D: cell length $D = \varphi \cdot c/\omega$ φ: phase advance per cell

$$\Gamma = \frac{(\beta-1)(\beta+1) - Q_0^2(\Delta F)^2}{(\beta+1)^2 + Q_0^2(\Delta F)^2} - j\frac{2\beta Q_0 \Delta F}{(\beta+1)^2 + Q_0^2(\Delta F)^2}$$

Imaginary part

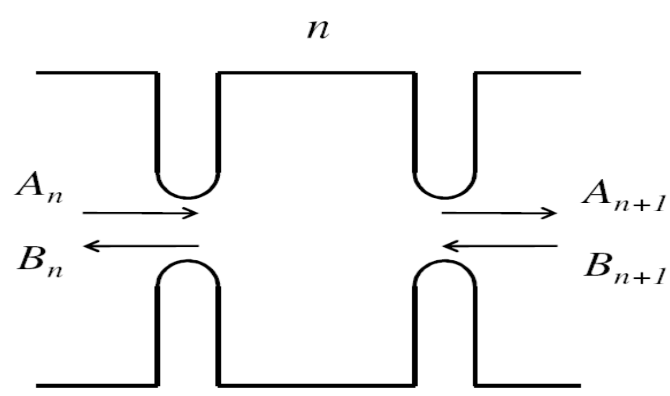
$$\Rightarrow \quad \Gamma \approx -j\frac{2\beta Q_0' \Delta F}{(\beta+1)^2 + {Q_0'}^2(\Delta F)^2} \approx j\frac{Q_0' \Delta f_0}{f_0}$$

Get the local reflection of each cell

- The wave

$$A_n = Ae^{j(\omega t - \varphi n)}$$

$$B_n = Be^{j(\omega t + \varphi n)}$$



- The field

$$I_{n-1} = A_n e^{j\varphi_{n-1}} + B_n e^{-j\varphi_{n-1}}$$

$$I_n = A_n + B_n$$

$$\Rightarrow \quad A_n = \frac{I_{n-1} + I_n e^{-j\varphi_{n-1}}}{-2j \sin \varphi_{n-1}}$$

$$B_n = \frac{I_{n-1} + I_n e^{j\varphi_{n-1}}}{2j \sin \varphi_{n-1}}$$

$$\Rightarrow \quad \Gamma_{\text{local}} = \frac{B_n - B_{n+1} e^{-j\varphi}}{A_n}$$

$$\Gamma_{\text{local}} = \frac{B_N}{A_N}$$

Output

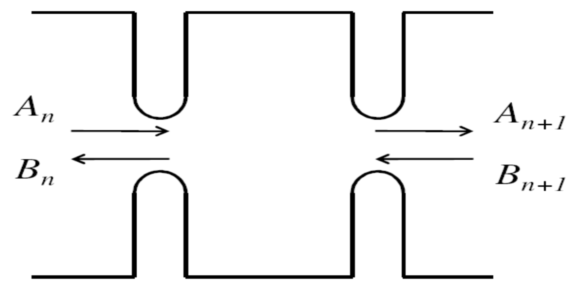
The reflection seen from the input coupler

- Loss in the structure / attenuation

$$|\Delta\Gamma_{\text{global}}| = e^{\alpha(n)}\,|\Delta\Gamma_{\text{local}}(n)|$$

Γ_{global}

$$\frac{\mathrm{d}P}{\mathrm{d}z} = -\frac{\omega}{Q_0}\frac{1}{v_g}P$$



$$P = P_0 \exp\left(-\int \frac{\omega}{Q_0 v_g}\mathrm{d}z\right)$$

$$\alpha(n) = -\frac{1}{2}\cdot 2\cdot\int_0^{(n-1)D}\frac{\omega}{Q_0 v_g}\mathrm{d}z.$$

$$\alpha(n) = -\sum_{m=1}^{n-1}\frac{c\varphi}{Q_0(m)v_g(m)}$$

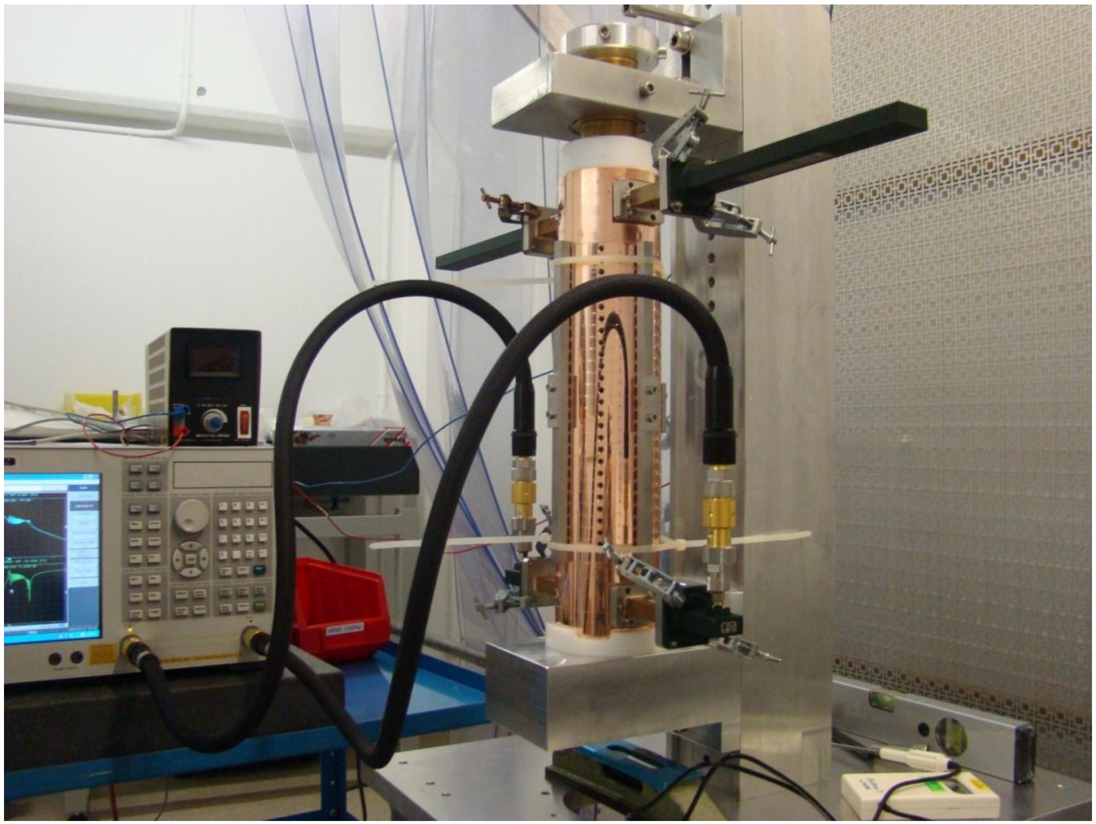
Forward and backward

Power to Amplitude

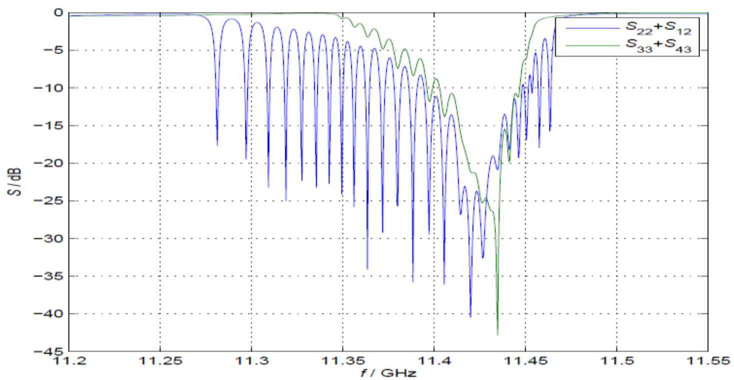
Summary of the method

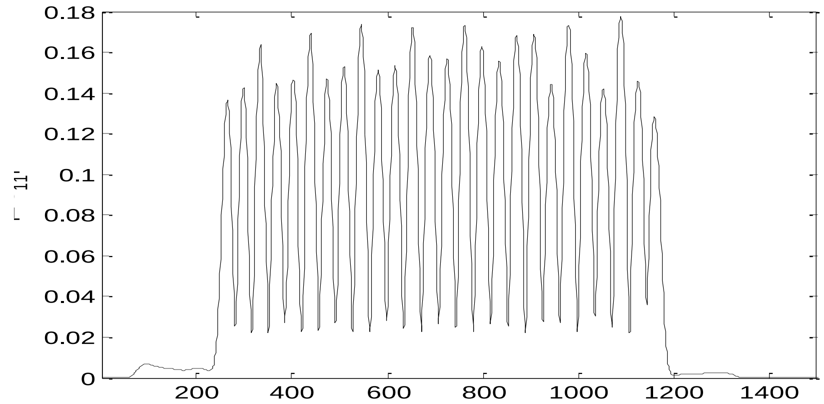
1. Do bead-pull measurement
2. Calculate forward and backward wave along the structure
3. Calculate local reflection of each cell
4. Calculate global reflection change due to local reflection change
5. Tuning each cell while monitoring the global reflection
    1. Start from output side
    2. Several iteration
6. Tuning the input cell to a minimum reflection

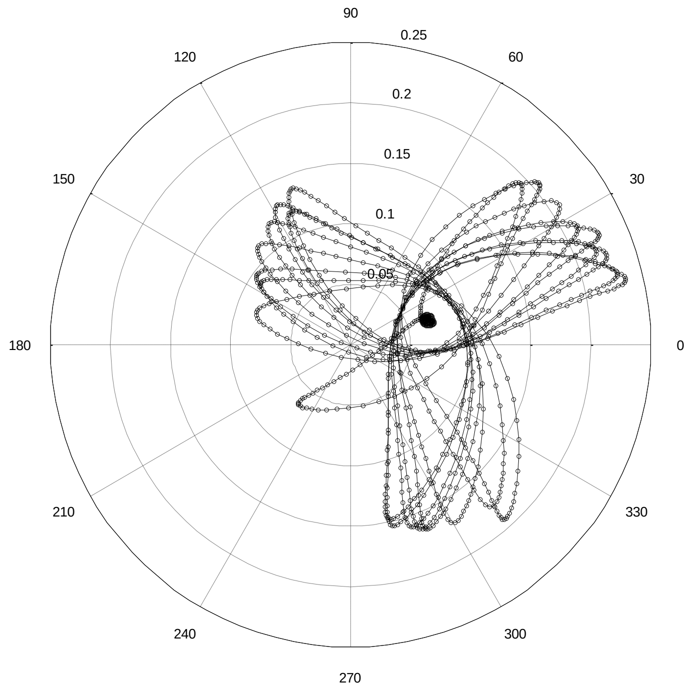
CLIC-G (TD24) N2 at 11.424 GHz

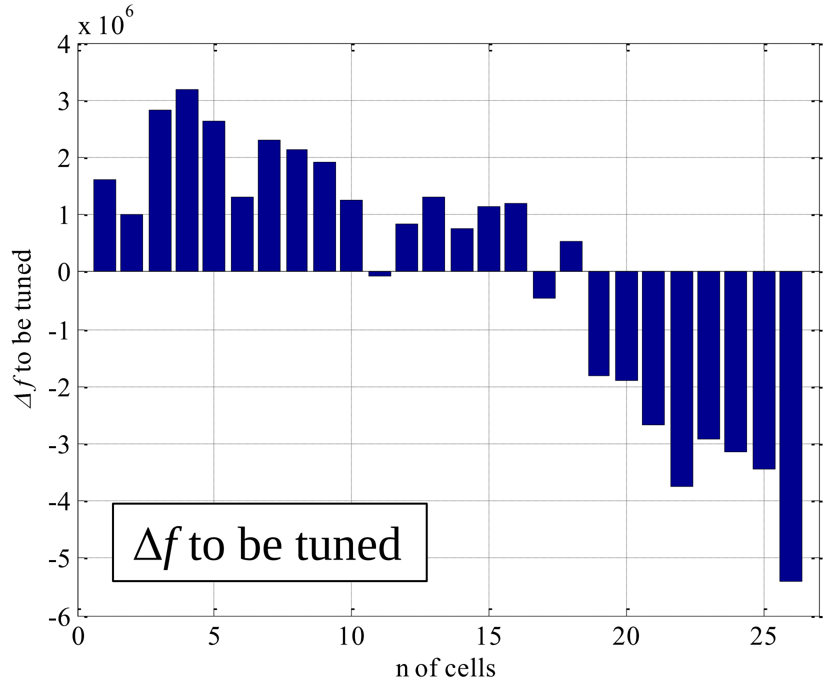


First diagnose

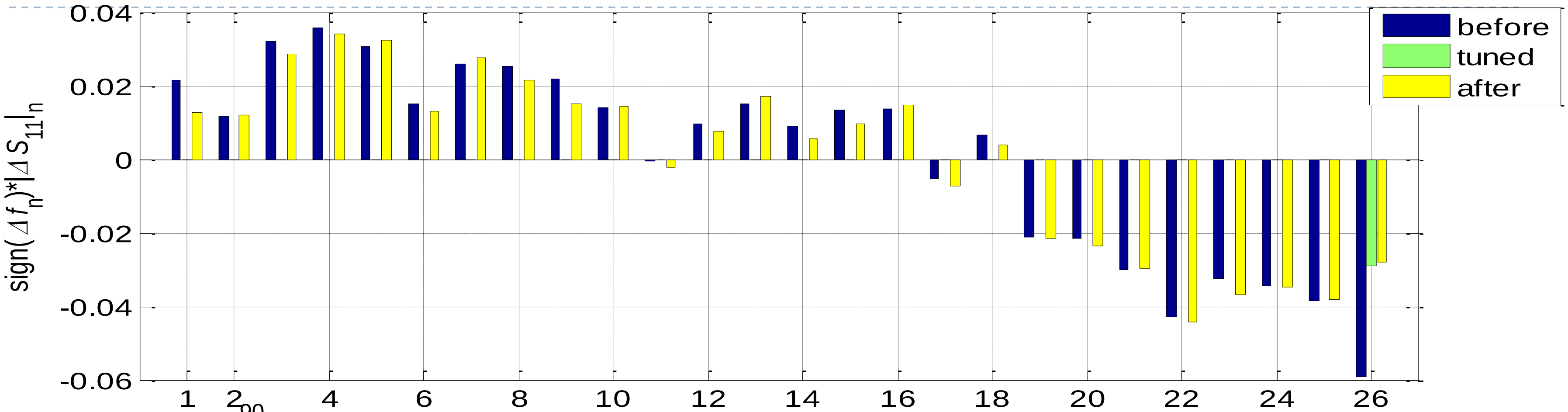


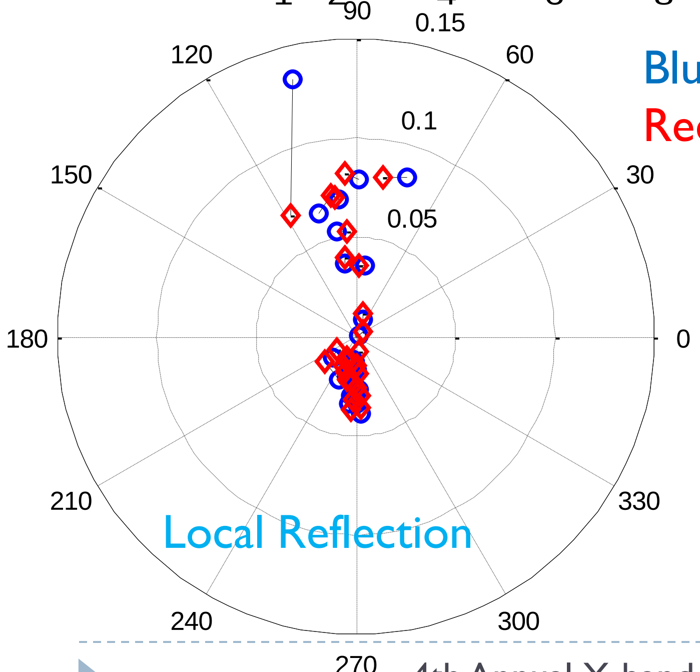




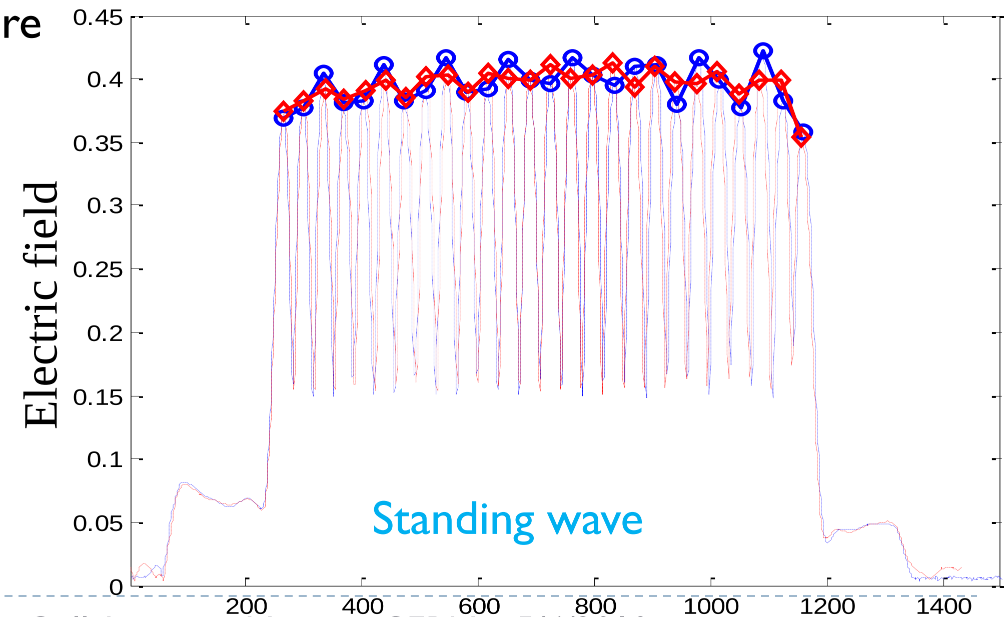


First tuning (the output matching cell)



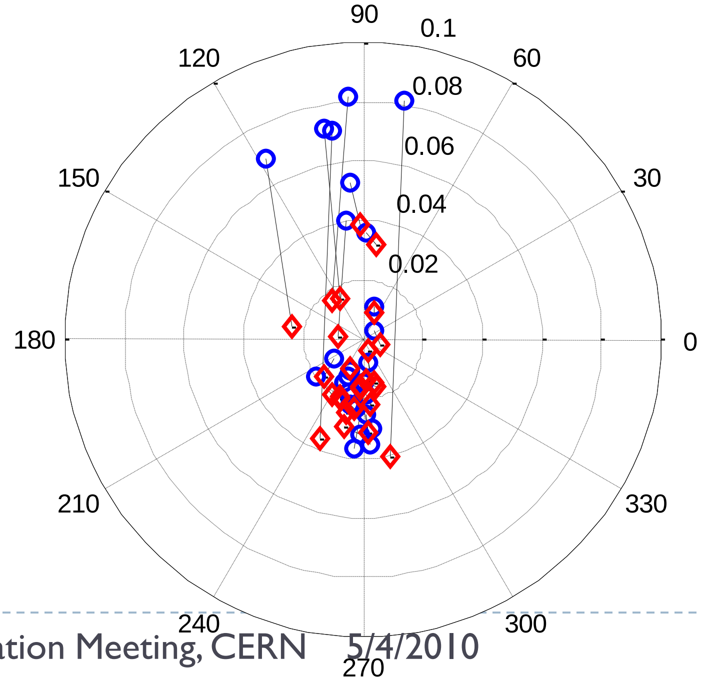


Blue: before
Red: after



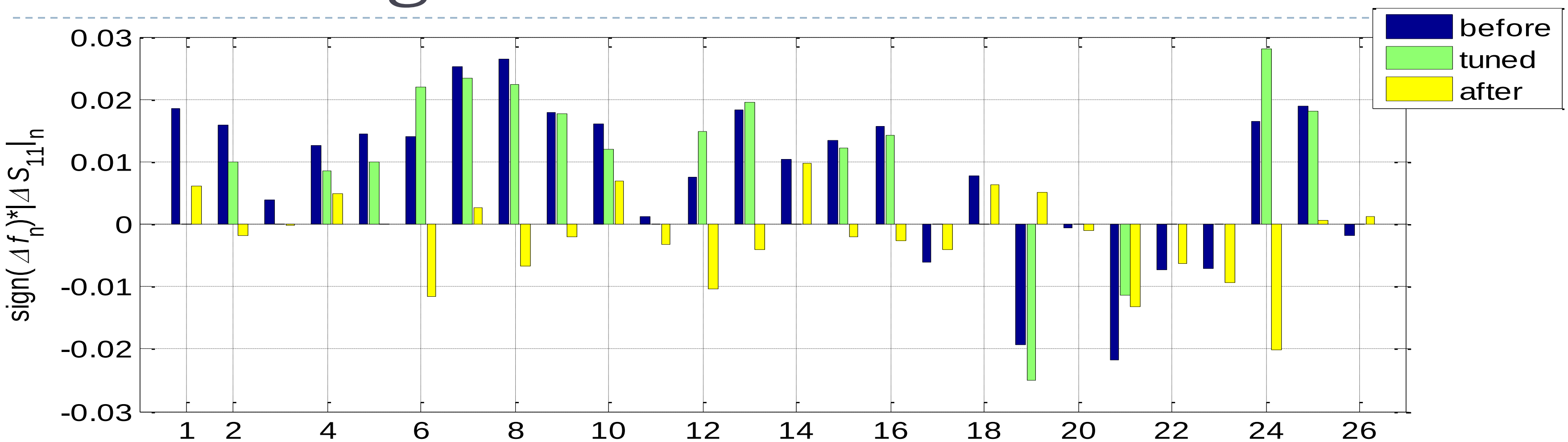
2nd tuning (10 worst cells)

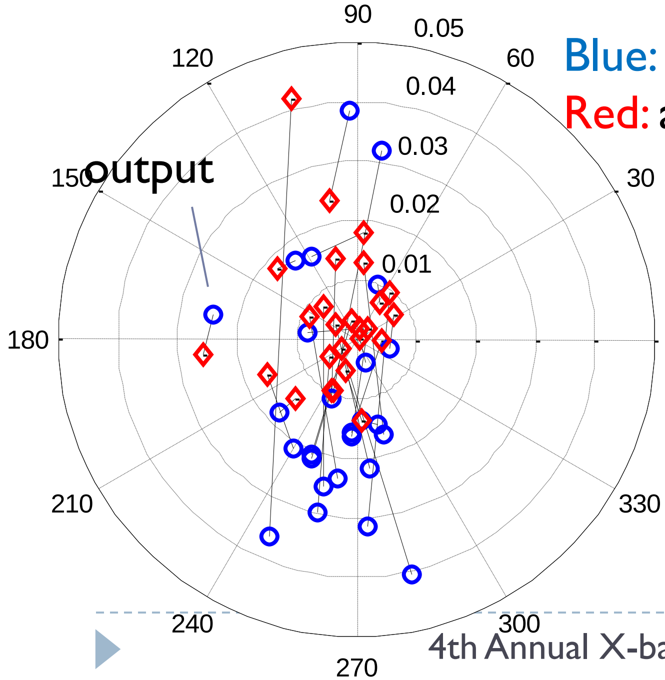
Blue: before
Red: after



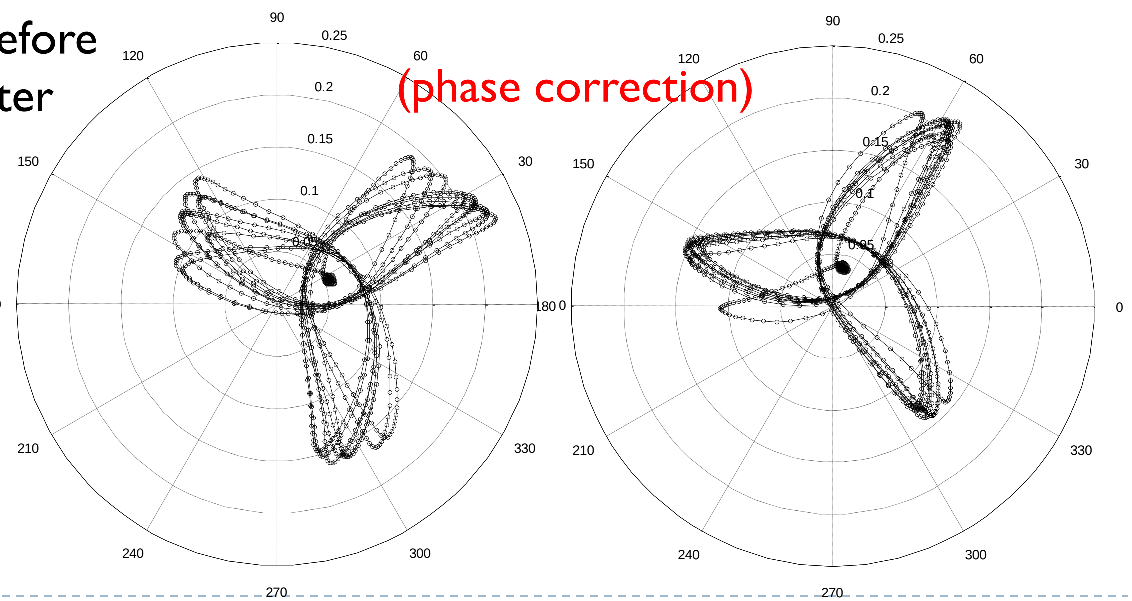
Local Reflection

3rd tuning

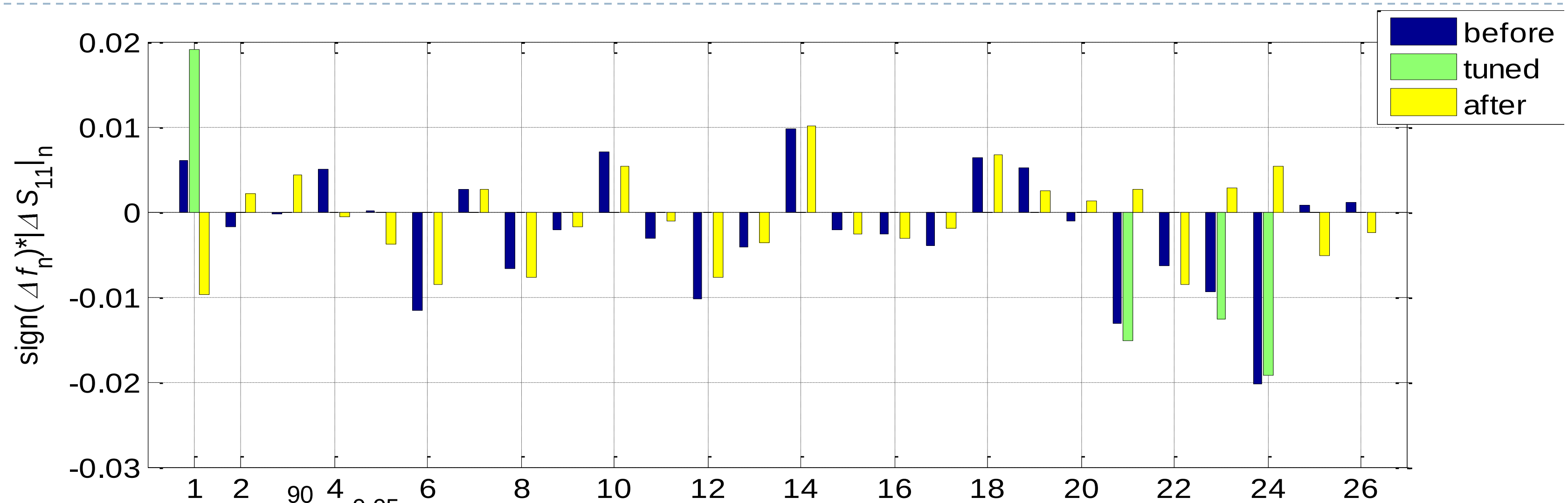


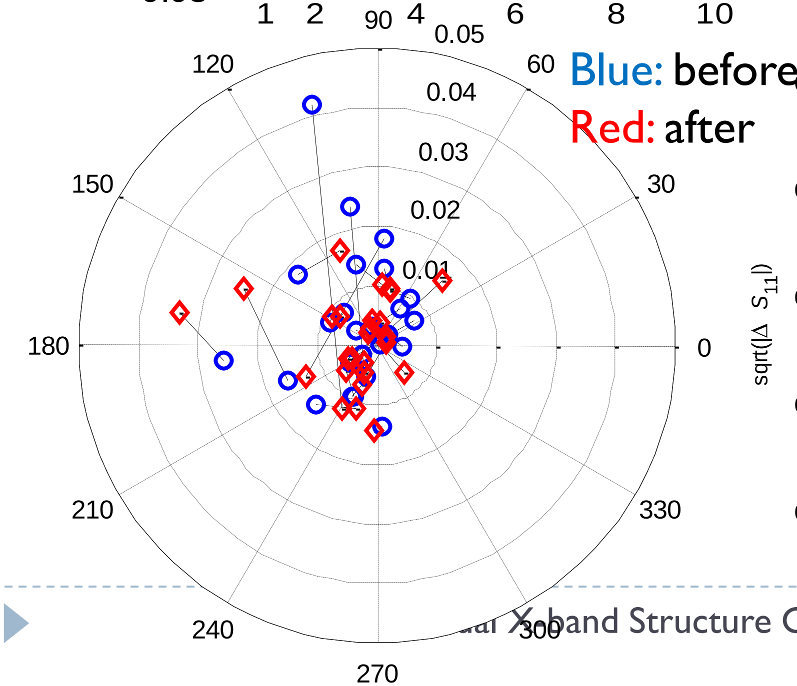


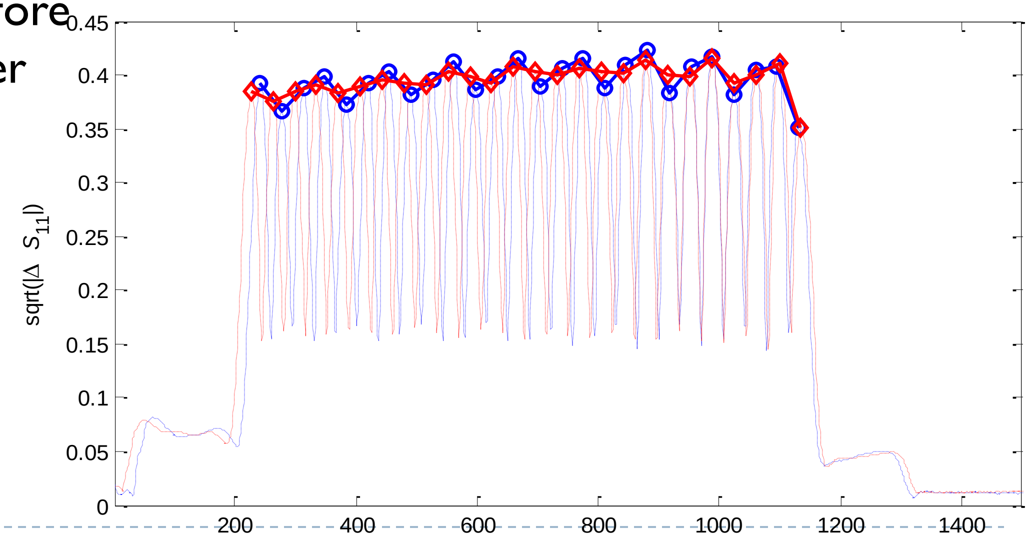
Blue: before
Red: after



4th tuning and the input matching cell





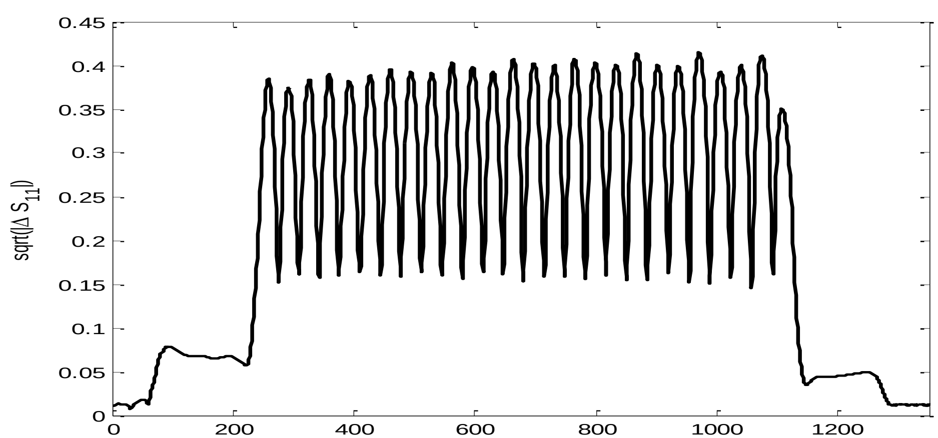


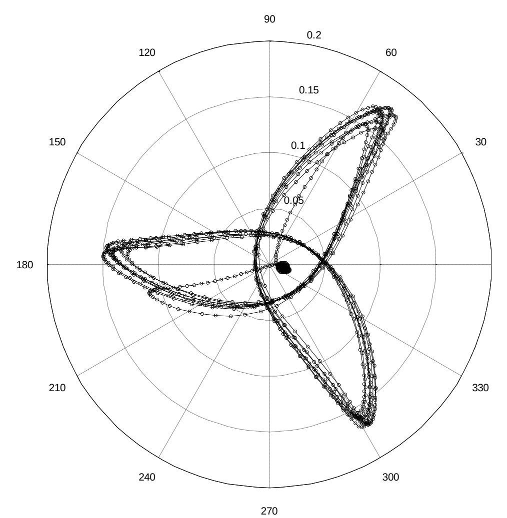
Summary of Tuning TD24

- Measurement condition

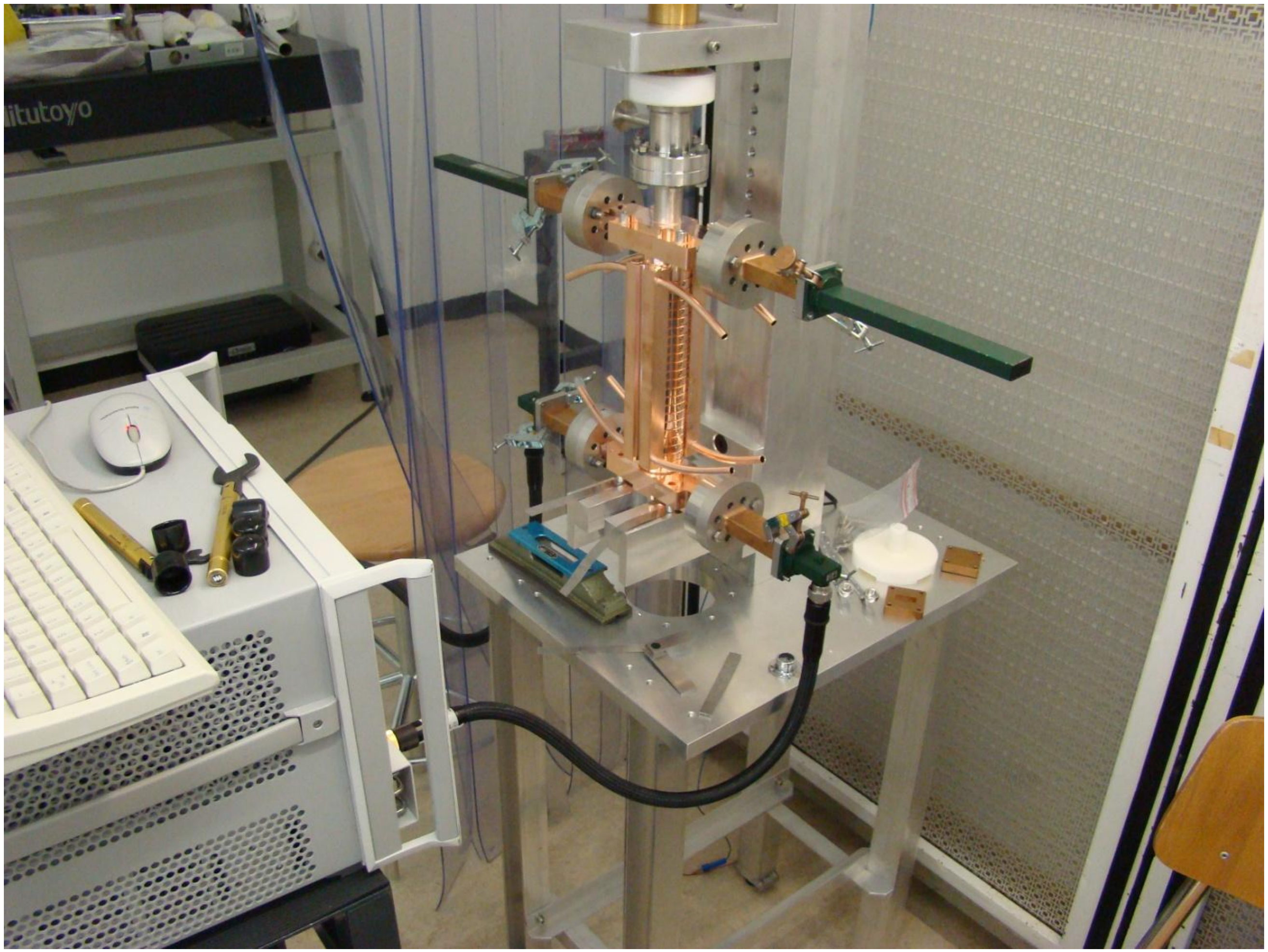
date :	19-Mar-2010
location:	CERN
VNA Model:	Agilent E5710C
temperature:	20.5°C
Designed frequency at $2\pi/3$:	11.424 GHz
High-power temperature:	30°C
Δf due to air $\Rightarrow$ vacuum:	+3.3 MHz
20.5°C $\Rightarrow$ 30°C:	−1.8 MHz
w/ $\Rightarrow$ w/o wire:	−0.3 MHz
(total):	+1.2 MHz
Target f under measurement condition (w/ wire, air, 20.5°C):	11422.8 MHz

- Push and Pull are applied in 4 iterations
- Maximum frequency correction ~6MHz
- Phase adv 120.1 / cell
- Standing-wave from output reflection (real part)

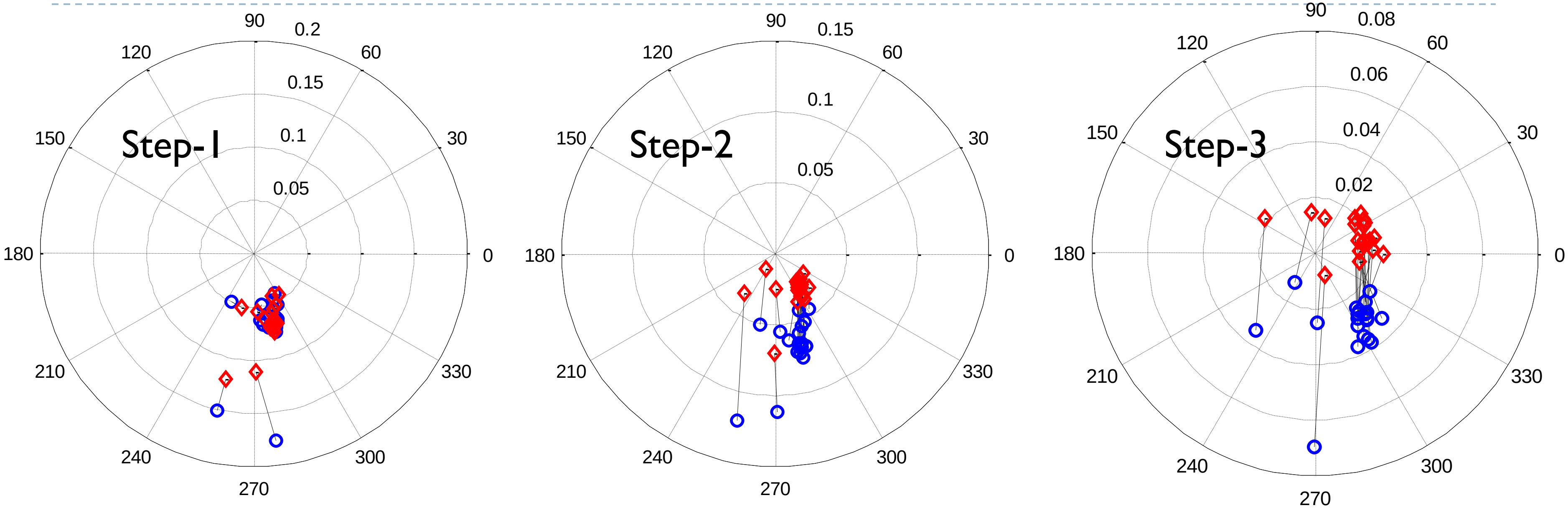




T18



T18

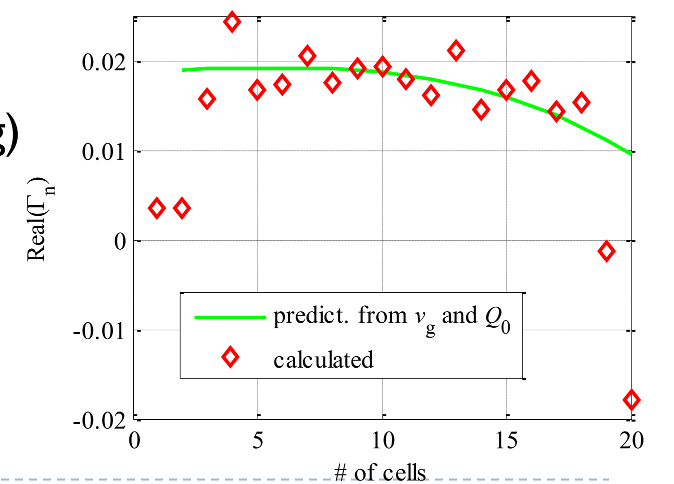


Local reflection of each cell

Blue: before tuning

Red: after tuning

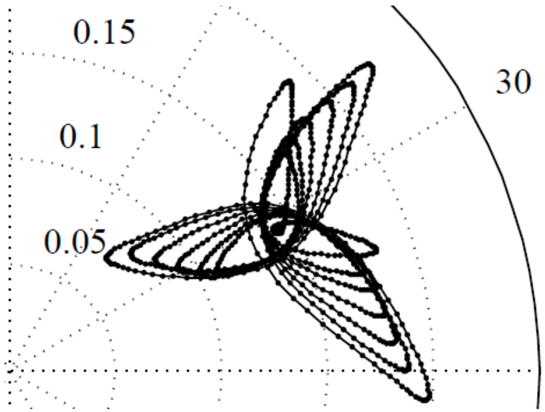
Real part: from tapering (vg)

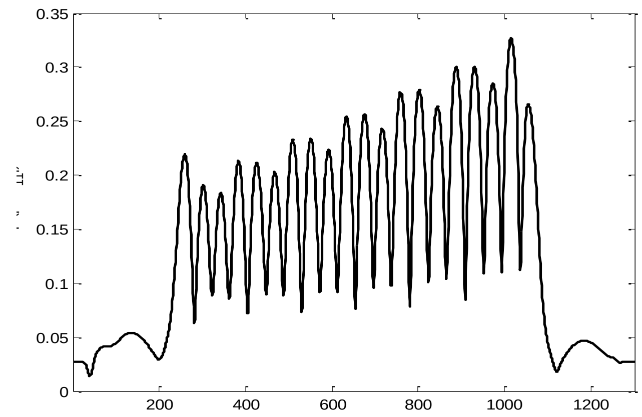


$$\Gamma = \boxed{\frac{(\beta-1)(\beta+1) - Q_0^2(\Delta F)^2}{(\beta+1)^2 + Q_0^2(\Delta F)^2}} - j\frac{2\beta Q_0 \Delta F}{(\beta+1)^2 + Q_0^2(\Delta F)^2}$$

Summary of Tuning T18

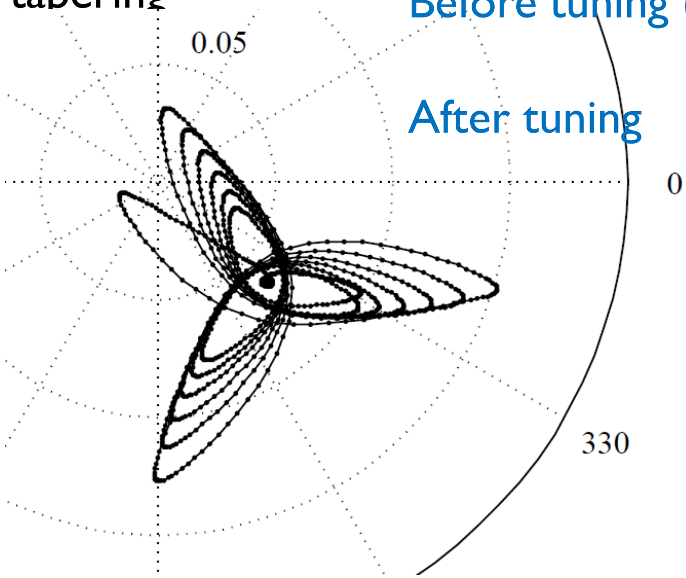
- To SLAC Temperature
- Only push, 3-steps
  - Output 8 MHz
  - Input 20 MHz !
  - Regular cells 3~6 MHz
- phi = 119.9
- Real part from tapering

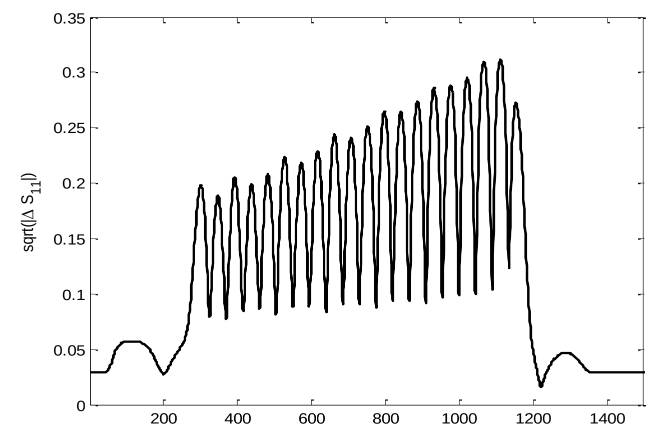




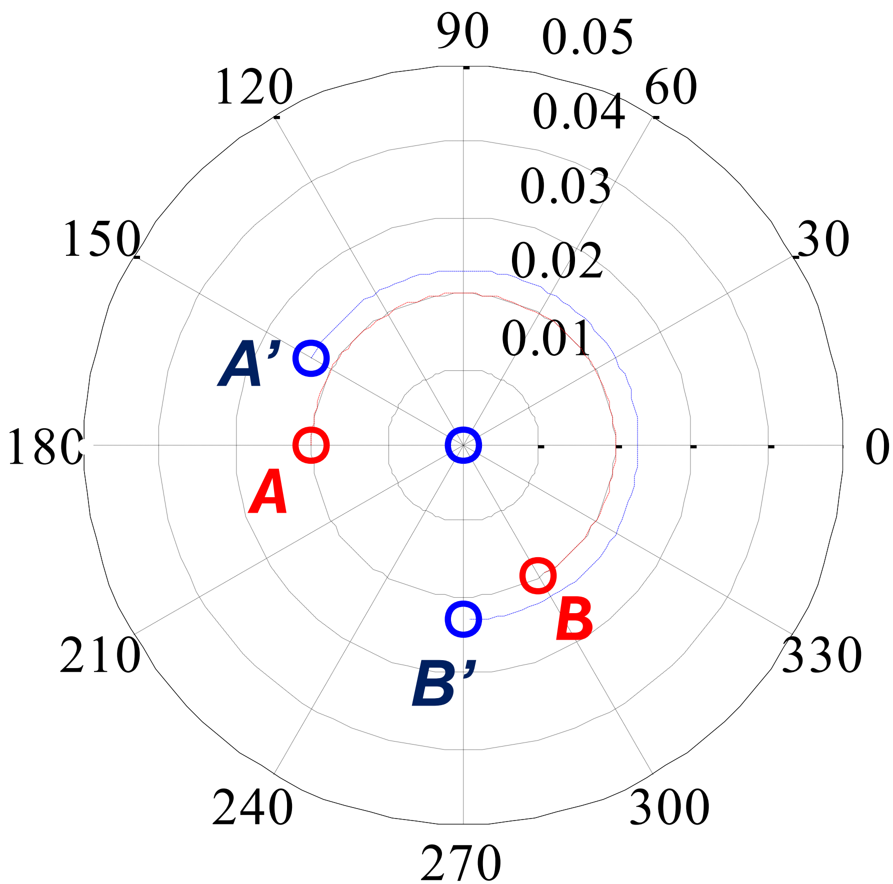
Before tuning (4MHz lower) ^^^

After tuning





Compensate output coupling (proposal)



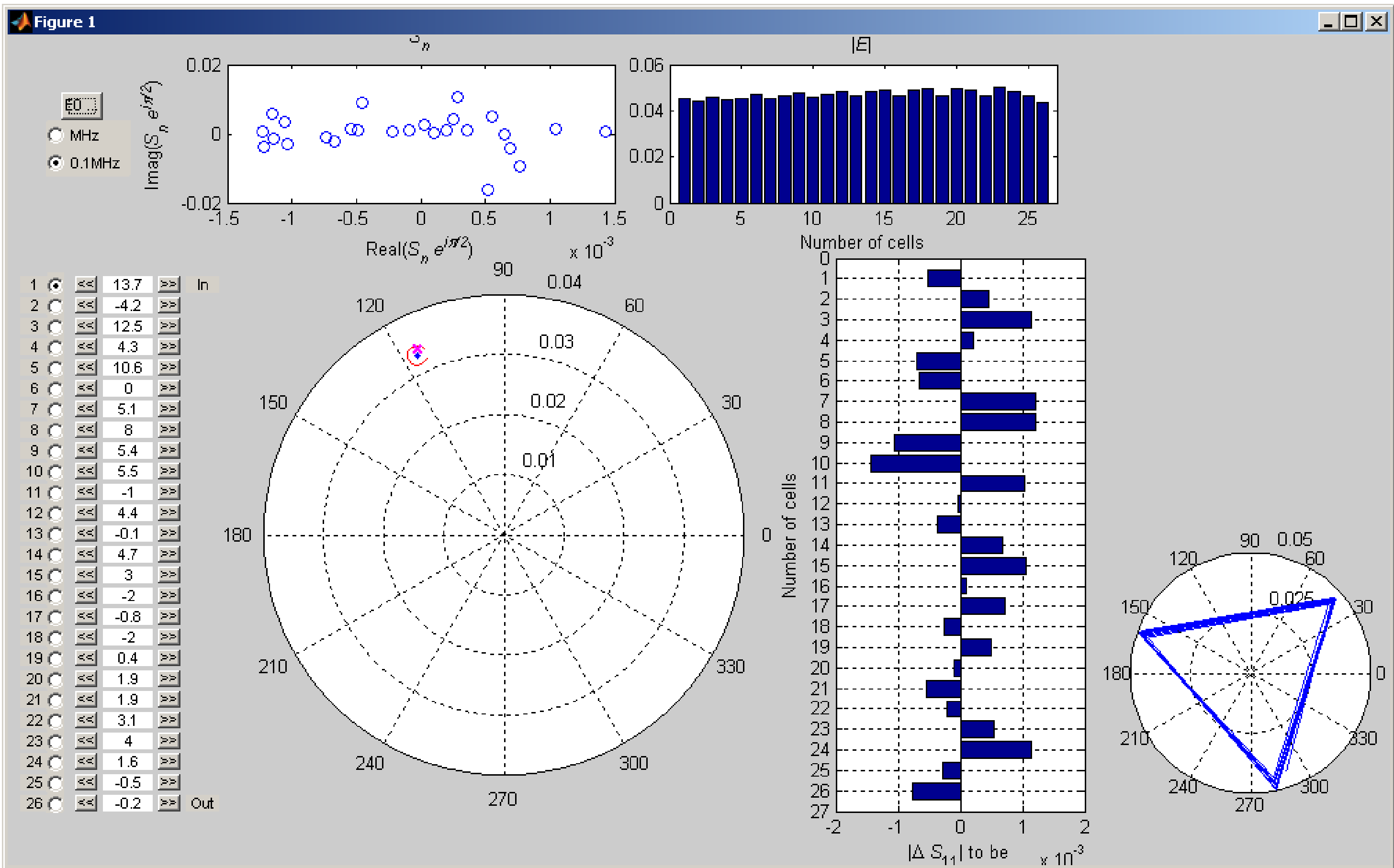
- The Points
  - *A*: Reflection of output matching cell (Γ_N) due to coupling iris error
  - *B*: Γ_N seen at *N*-1 Cell
  - *A'*: Reflection from detuned output cell $\Gamma_N{}'$
  - *B'*: $\Gamma_N{}'$ seen at *N*-1 Cell
  - *O*: $\Gamma_N{}'$ can be cancelled by detuning the *N*-1 Cell
- High accuracy required

Summary

- Accuracy
  - 0.005 (-45dB) for local reflection (from experience)
  - The model
    - vg along the structure is important
    - Calculation of the output matching cell is not so accurate because of the different cell shape
    - Calculation of the input matching cell need to correct the phase (use bead perturbation as reference), the last to tune.
  - The real part of the local reflection can not be corrected
    - From Tapering. Good agreement!
    - Output matching iris error cause standing wave. May be compensated by detuning the #(N-1) and the output cell

Summary

- Integrated software tool under development



Thank you!