Some Consideration on Cavity Turn on and Cavity Test

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Introduction

This talk is focusing on and trying to find suitable solutions for the issues and tough facts expected to face for cavity operation and maintenance.

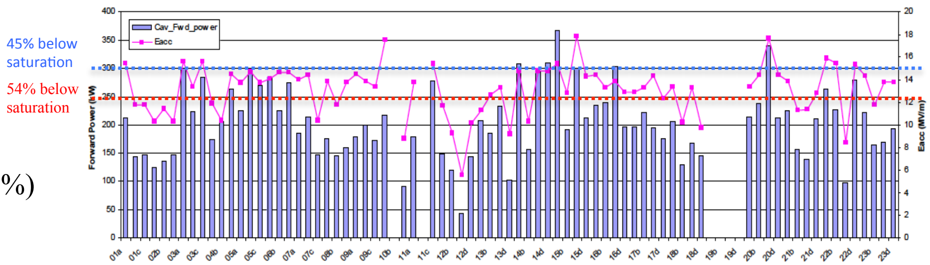
- ✓ **How to deal with the new challenges: longer pulse, higher beam intensity, higher beam power, higher gradient, spoke cavities and high demands for energy efficiency and availability.**

- ✓ **How to deal with wide spread of cavity parameters: maximum operable gradient, Q_L, Lorentz force detuning coefficients, major mechanical modes, etc.**

- ✓ **How to learn as much as possible from a variety of RF tests carried out at different test stands and final accelerator tunnel, in order to better understand the cavity system and know its limitations, thereby operating the cavity system efficiently and effectively.**

Facing Up to New Challenges at ESS

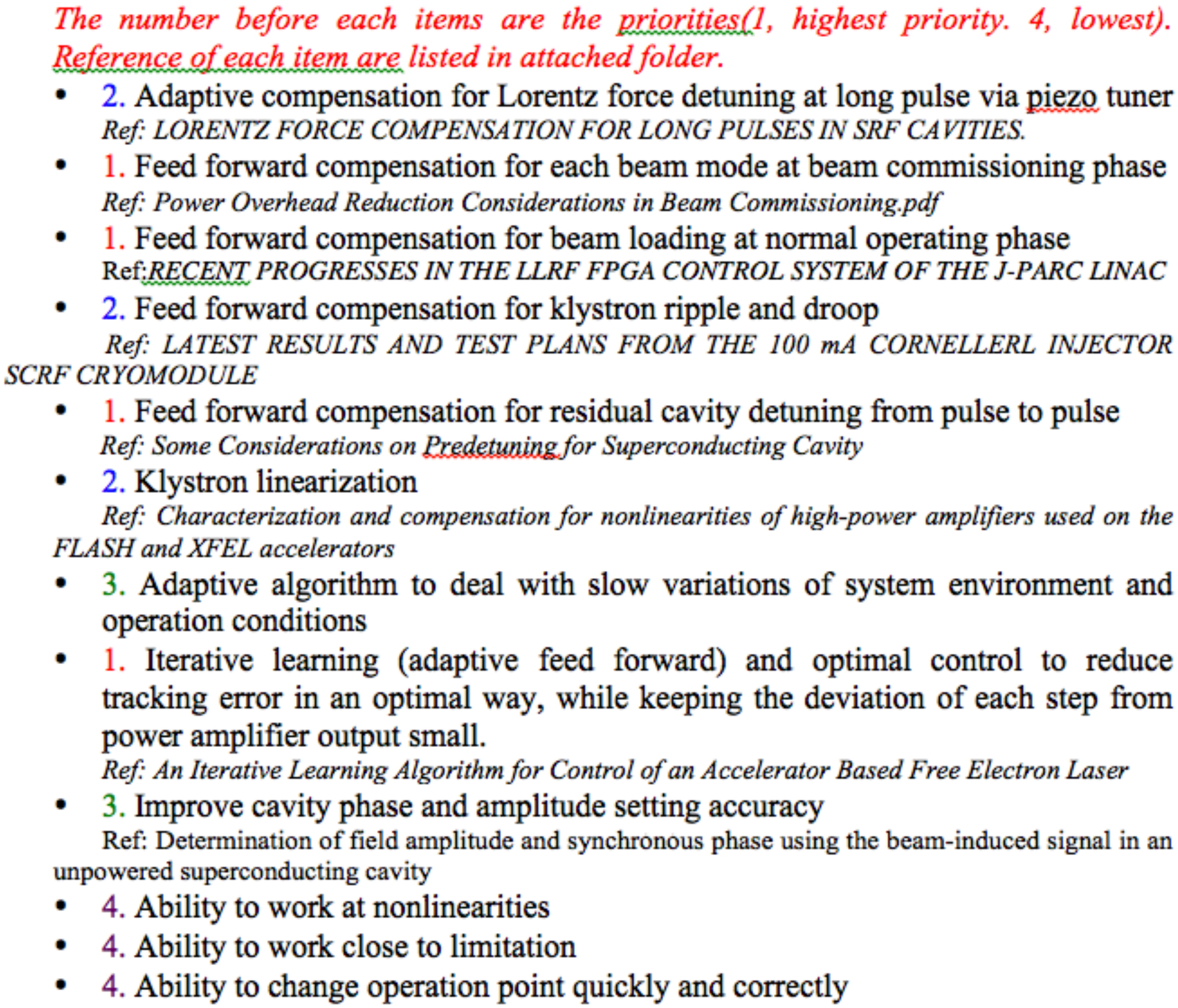
- **Long pulse(~3.5ms RF pulses)**
  - Much longer Lorentz force detuning dynamics during pulse, might not be able to get compensated by traditional way driving the piezo with a simple half-cycle sinusoid impulse
  - Klystron output droop and ripple might be bigger due to long RF pulse
- **High intensity**
  - Heavy beam beam loading in cavities, require careful feedforward compensation for each beam mode during pulses, and appropriate adaptive feedforward to reduce the repetitive feedback transient response from pulse to pulse
- **High gradient**
  - High Lorentz force detuning; Work close to the quench limitation
- **High beam power**
  - The same situation of RF setting errors (up to 2° in phase and 2% in amplitude) might not be acceptable at ESS due to probably higher beam loss at high power linac of 5MW
- **Spoke cavity**
  - Uncertainties;
- **Energy Efficient**
  - Klystron Linearization;
  - Minimize RF power overhead for RF control(25%→10%)
- **High availability**
  - Fast recovery from quench;
  - Fast recovery from single/multiple LLRF, klystron, modulator, cavity, cryomodule failures



Advantage at ESS

- One Cavity per power amplifier(klystron, Tetrod, IOT…)
- most are cold linac
- cavity field stability not high (1%, 1 deg.)
- high cavity bandwidth
- powerful new technology: 10 input channel (2.5 times as SNS), ~1000 times bigger memory in FPGA, and faster CPU, communication…

Possible solutions



The number before each items are the priorities(1, highest priority. 4, lowest). Reference of each item are listed in attached folder.

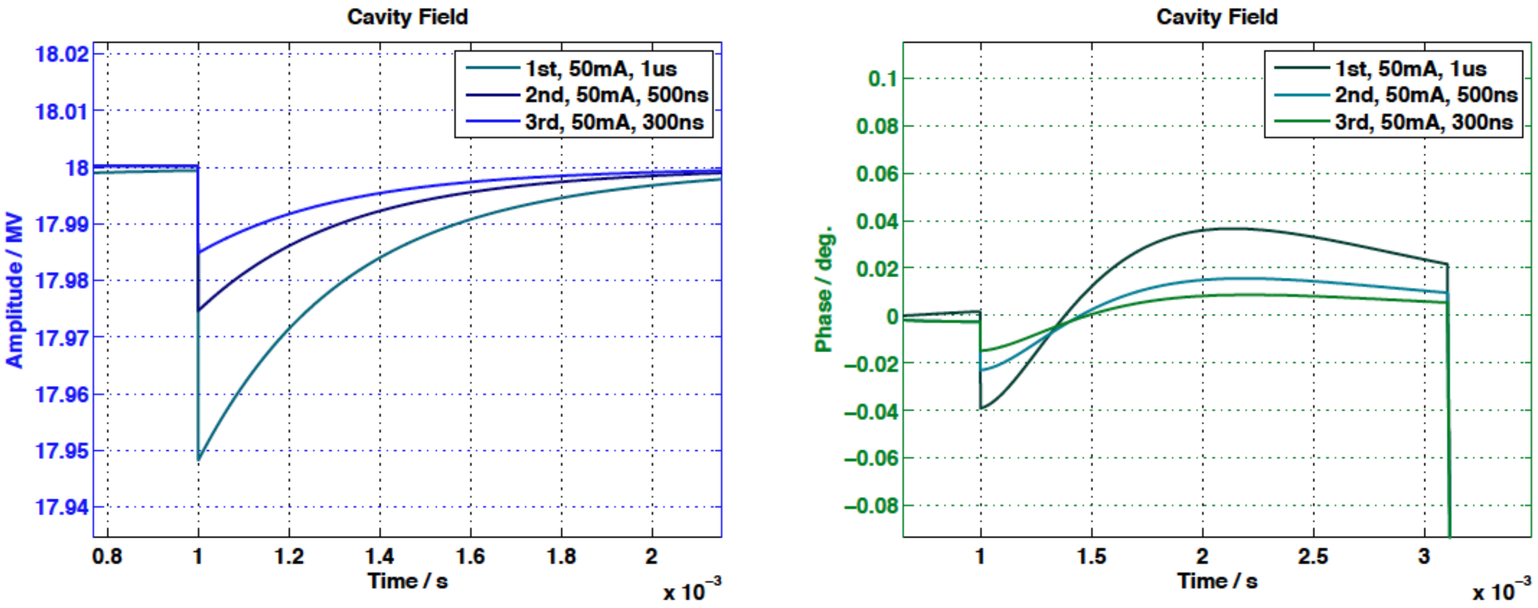
- 2. Adaptive compensation for Lorentz force detuning at long pulse via piezo tuner
  Ref: LORENTZ FORCE COMPENSATION FOR LONG PULSES IN SRF CAVITIES.
- 1. Feed forward compensation for each beam mode at beam commissioning phase
  Ref: Power Overhead Reduction Considerations in Beam Commissioning.pdf
- 1. Feed forward compensation for beam loading at normal operating phase
  Ref:*RECENT PROGRESSES IN THE LLRF FPGA CONTROL SYSTEM OF THE J-PARC LINAC*
- 2. Feed forward compensation for klystron ripple and droop
  Ref: LATEST RESULTS AND TEST PLANS FROM THE 100 mA CORNELLERL INJECTOR SCRF CRYOMODULE
- 1. Feed forward compensation for residual cavity detuning from pulse to pulse
  Ref: Some Considerations on Predetuning for Superconducting Cavity
- 2. Klystron linearization
  Ref: Characterization and compensation for nonlinearities of high-power amplifiers used on the FLASH and XFEL accelerators
- 3. Adaptive algorithm to deal with slow variations of system environment and operation conditions
- 1. Iterative learning (adaptive feed forward) and optimal control to reduce tracking error in an optimal way, while keeping the deviation of each step from power amplifier output small.
  Ref: An Iterative Learning Algorithm for Control of an Accelerator Based Free Electron Laser
- 3. Improve cavity phase and amplitude setting accuracy
  Ref: Determination of field amplitude and synchronous phase using the beam-induced signal in an unpowered superconducting cavity
- 4. Ability to work at nonlinearities
- 4. Ability to work close to limitation
- 4. Ability to change operation point quickly and correctly

The way to go…

- Have adequate and high quality data (high resolution, data completeness, get data as we required)
- Carry out elaborate experimentation and make accurate measurement to obtain required data for particular purpose
- Develop sophisticated models to identify system mechanism, predict system behaviors and find out system limitation

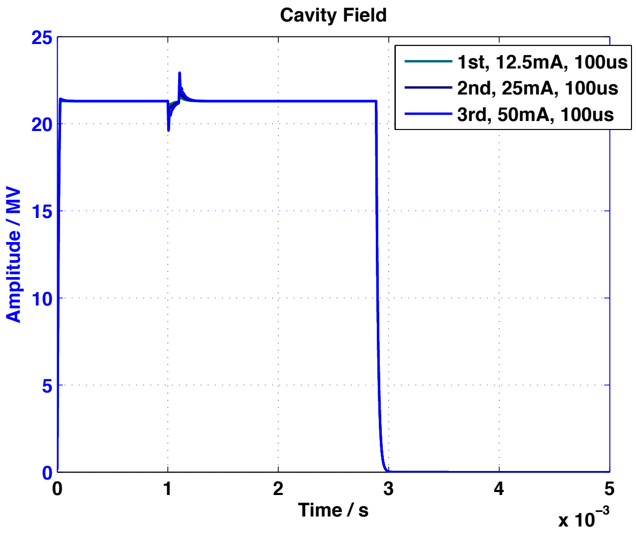
Higher Resolution: What happen during 1us

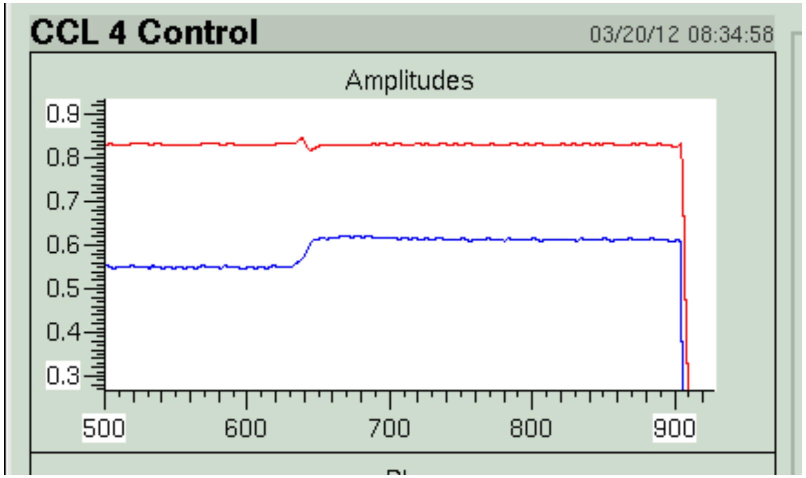
- ✓ 52.7kV (0.29% of operating voltage 18MV) for the 1μs-long beam pulse induced voltage



Worse at normal conducting cavity

- ✓ Normal conducting cavities (RFQ, DTL) have much lower Ql, ~ factor of 30.
- ✓ Control is much more difficult due to low loop gain (~2, compared to 50 in superconducting cavity)
- ✓ Beam loading is a very high frequency perturbations, and cannot be well compensated by integral controller

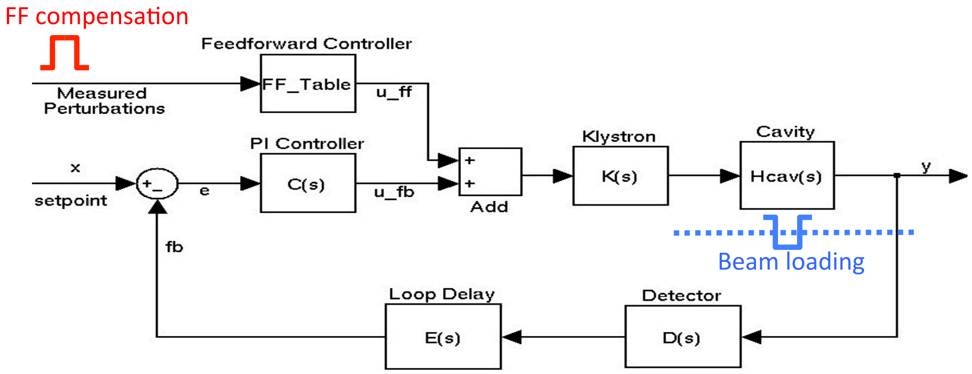


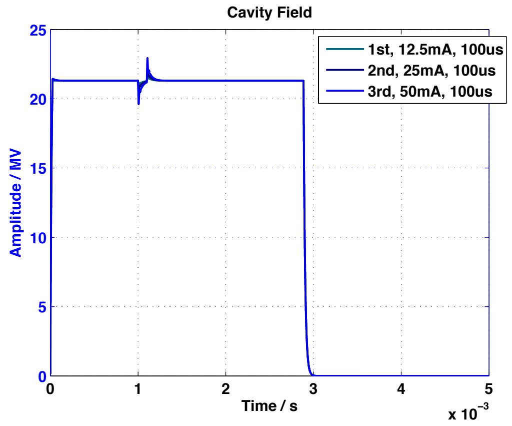


from presentation of J. Galambos

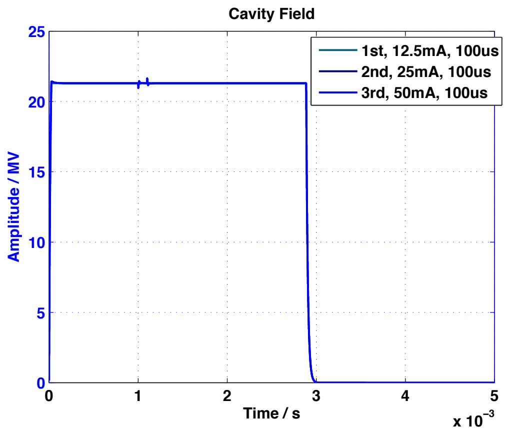
Higher resolution

- ✓ Feed forward table adjustable resolution (better performance when resolution <100ns.
- ✓ Exp. If designed beam arriving time for high beta relative to RF pulse is 243.6 us, for 1us resolution, FF table can only adjust with 243us or 244us)

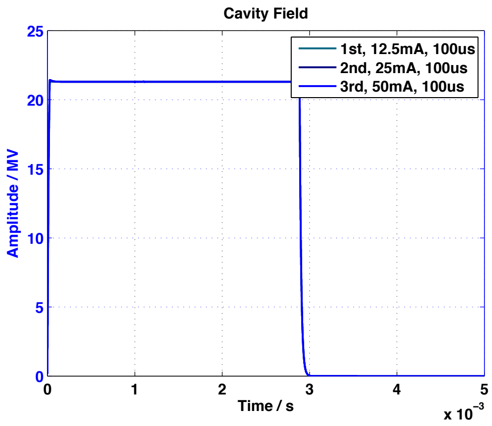




Without FF compensation
Error: ±7%

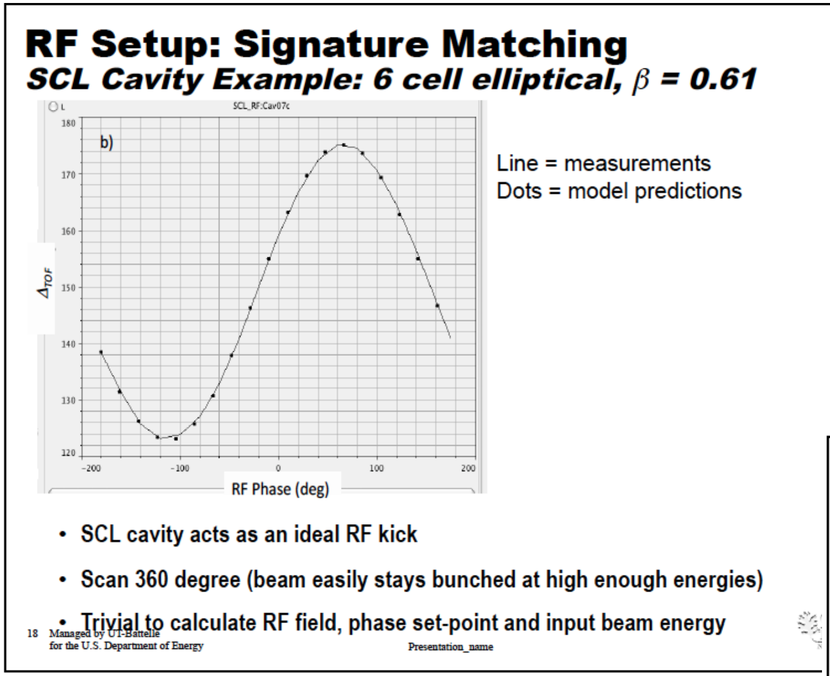


resolution: 1us
Field error: ±1.6%



resolution: 100ns
Field error: ±0.18%

Data Completeness: Beam based calibration



RF Setup: Signature Matching

SCL Cavity Example: 6 cell elliptical, β = 0.61

Line = measurements
Dots = model predictions

- SCL cavity acts as an ideal RF kick
- Scan 360 degree (beam easily stays bunched at high enough energies)
- Trivial to calculate RF field, phase set-point and input beam energy

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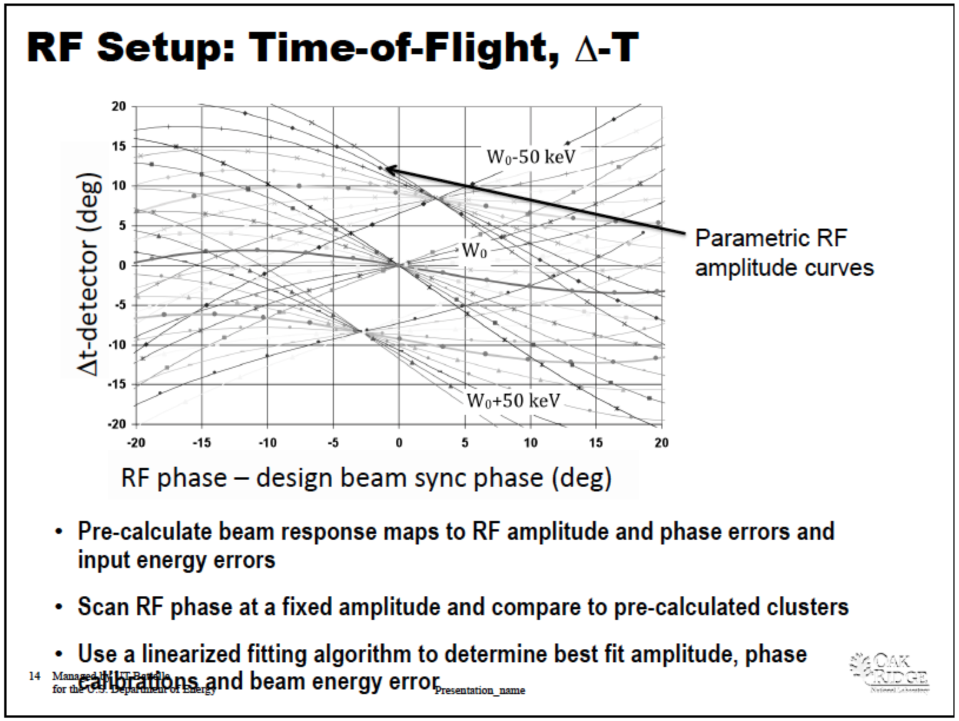
$$\Delta W = qE_0TL\cos\phi_{0,}$$

$$\Delta\phi = \frac{qE_0L}{mc^2\beta_1^2\gamma_1^3}kT'\sin\phi_0\,,$$

$$\phi_0 = \phi_1 + l_1\frac{d\phi_1}{dz} - \Delta\phi$$

$$\phi_1^+ = \phi_0 + l_2\frac{d\phi_0}{dz}$$



RF Setup: Time-of-Flight, Δ-T

Parametric RF amplitude curves

- Pre-calculate beam response maps to RF amplitude and phase errors and input energy errors
- Scan RF phase at a fixed amplitude and compare to pre-calculated clusters
- Use a linearized fitting algorithm to determine best fit amplitude, phase calibrations and beam energy error

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Data completeness: RF based calibration

$$\vec{V}_c = \vec{V}_{for} + \vec{V}_{ref}$$

$$\vec{V}_{for} = m\vec{V}_{for\_m}$$

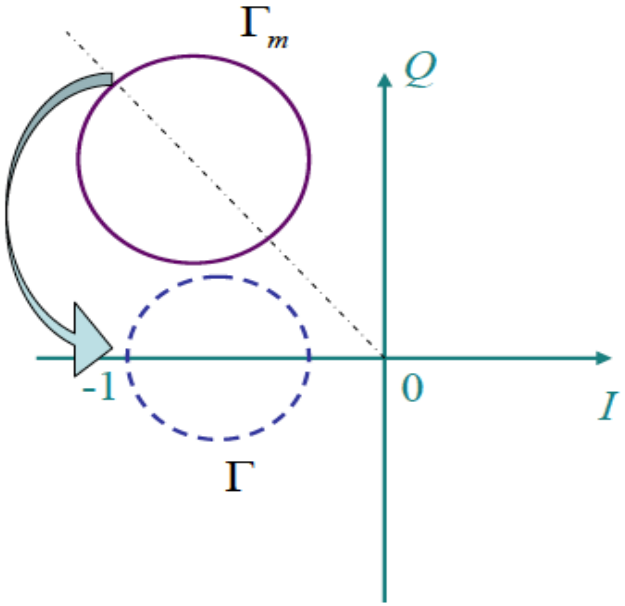
$$\vec{V}_{ref} = n\vec{V}_{ref\_m}$$

$$\vec{V}_c = m\vec{V}_{for\_m} + n\vec{V}_{ref\_m} = m\left(\vec{V}_{for\_m} + \frac{n}{m}\vec{V}_{ref\_m}\right)$$

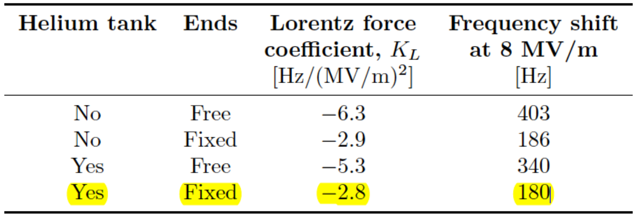
VSWR	Tao
1.00	0.000000
1.01	0.004975
1.02	0.009901
1.03	0.014778
1.04	0.019608
1.05	0.024390
1.06	0.029126
1.07	0.033816
1.08	0.038462
1.09	0.043062
1.10	0.047619
1.11	0.052133

$$\Gamma_m = \frac{\vec{V}_{ref\_m}}{\vec{V}_{for\_m}} = \left(\frac{2\beta}{\beta+1}\frac{\omega_{1/2}}{\omega_{1/2} - j\Delta\omega} - 1\right)\cdot\frac{m}{n}$$

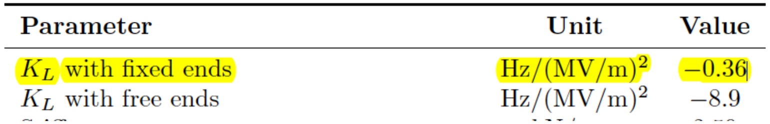
$$\Gamma = \frac{\vec{V}_{ref}}{\vec{V}_{for}} = \frac{2\beta}{\beta+1}\frac{\omega_{1/2}}{\omega_{1/2} - j\Delta\omega} - 1$$



Get data as we required



Helium tank	Ends	Lorentz force coefficient, K_L [Hz/(MV/m)^2]	Frequency shift at 8 MV/m [Hz]
No	Free	−6.3	403
No	Fixed	−2.9	186
Yes	Free	−5.3	340
Yes	Fixed	−2.8	180



Parameter	Unit	Value
K_L with fixed ends	Hz/(MV/m)^2	−0.36
K_L with free ends	Hz/(MV/m)^2	−8.9

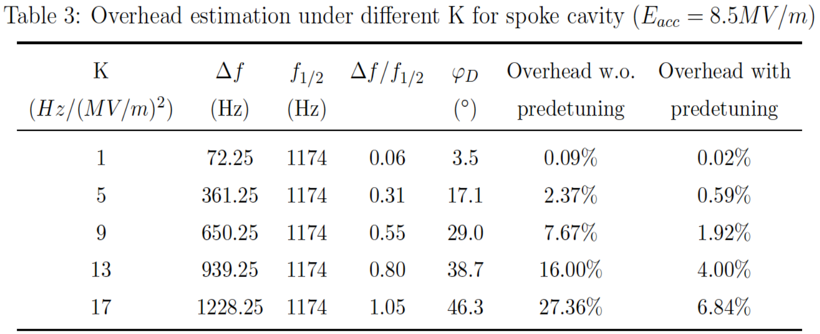


Table 3: Overhead estimation under different K for spoke cavity ($E_{acc} = 8.5MV/m$)

K $(Hz/(MV/m)^2)$	Δf (Hz)	$f_{1/2}$ (Hz)	$\Delta f/f_{1/2}$	φ_D (°)	Overhead w.o. predetuning	Overhead with predetuning
1	72.25	1174	0.06	3.5	0.09%	0.02%
5	361.25	1174	0.31	17.1	2.37%	0.59%
9	650.25	1174	0.55	29.0	7.67%	1.92%
13	939.25	1174	0.80	38.7	16.00%	4.00%
17	1228.25	1174	1.05	46.3	27.36%	6.84%

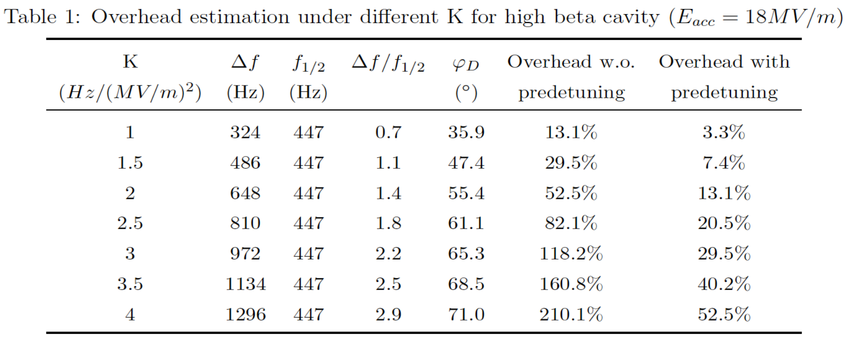
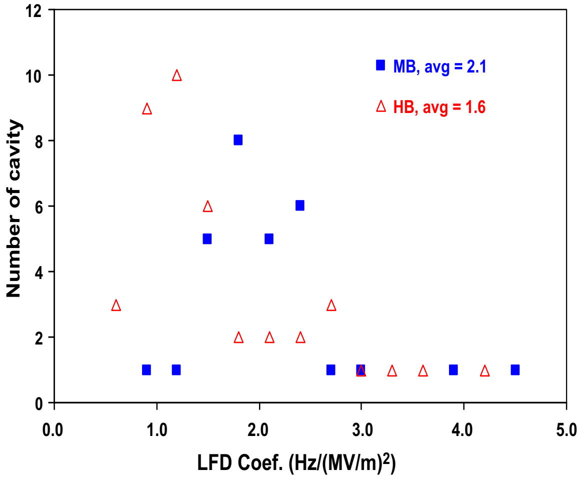
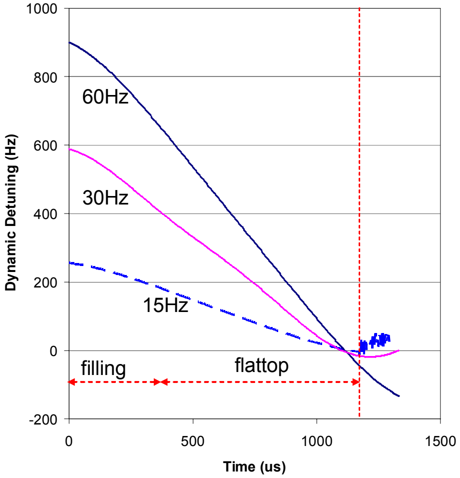


Table 1: Overhead estimation under different K for high beta cavity ($E_{acc} = 18MV/m$)

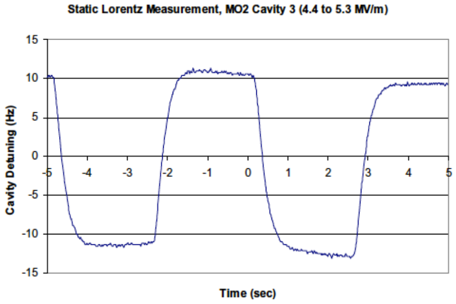
K $(Hz/(MV/m)^2)$	Δf (Hz)	$f_{1/2}$ (Hz)	$\Delta f/f_{1/2}$	φ_D (°)	Overhead w.o. predetuning	Overhead with predetuning
1	324	447	0.7	35.9	13.1%	3.3%
1.5	486	447	1.1	47.4	29.5%	7.4%
2	648	447	1.4	55.4	52.5%	13.1%
2.5	810	447	1.8	61.1	82.1%	20.5%
3	972	447	2.2	65.3	118.2%	29.5%
3.5	1134	447	2.5	68.5	160.8%	40.2%
4	1296	447	2.9	71.0	210.1%	52.5%

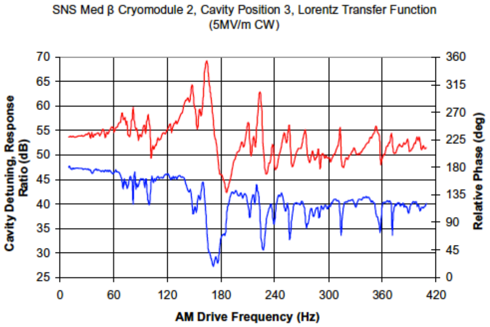




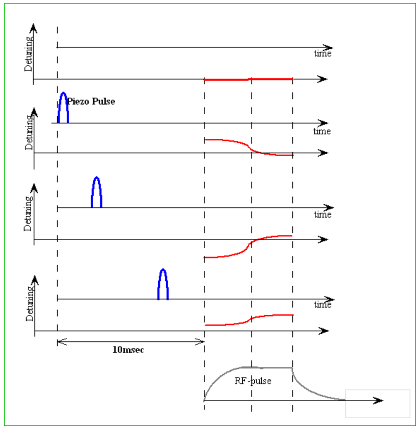
Get data as we required

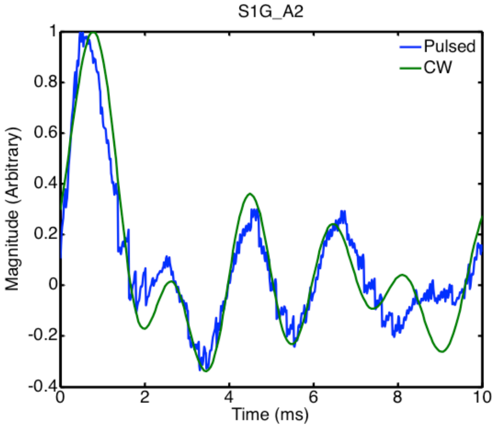
- ✓ Example: Lorentz Force Detuning Compensation
  - Static LFD coefficients
  - Dynamic LFD spectrum


Static Lorentz Measurement, MO2 Cavity 3 (4.4 to 5.3 MV/m)

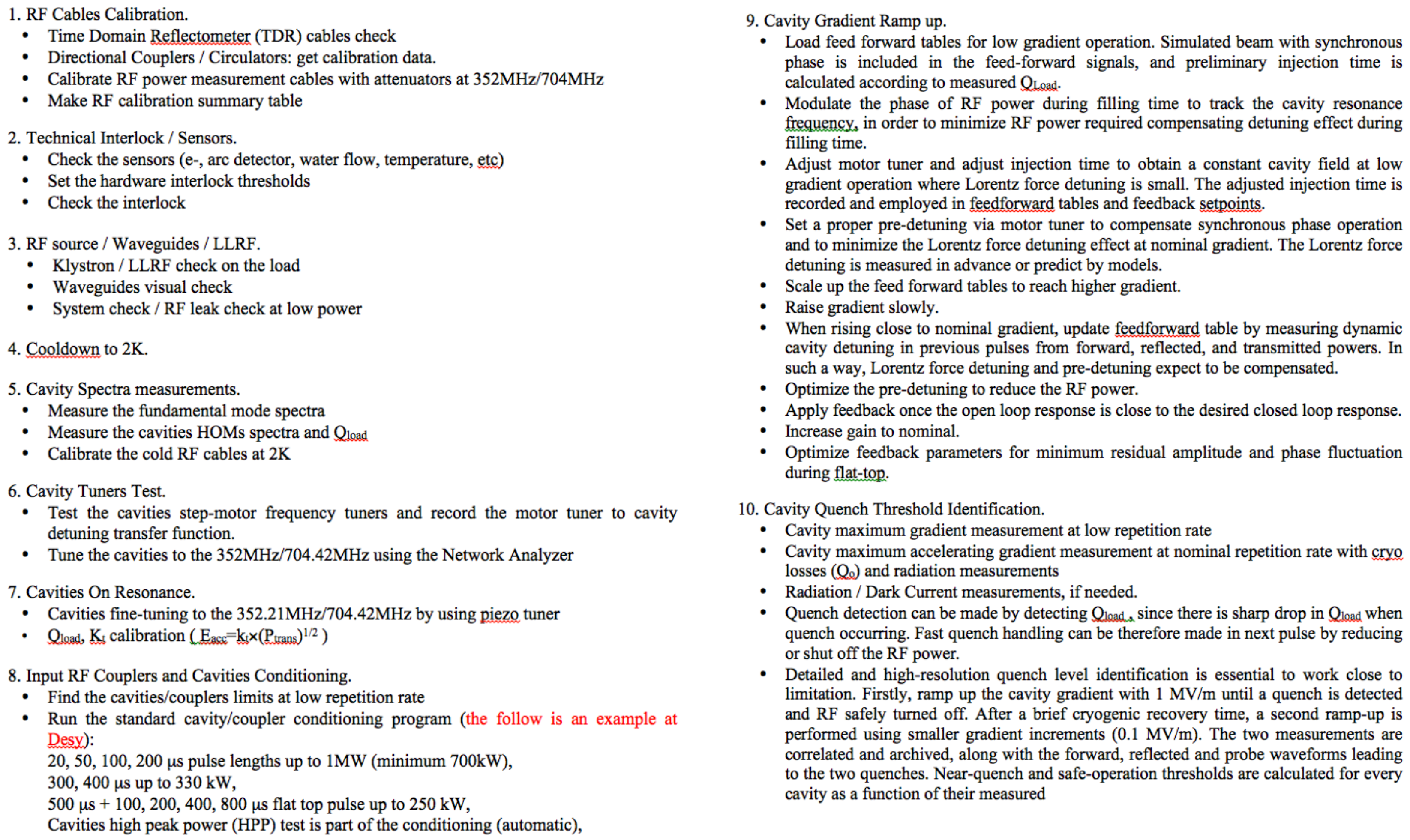

SNS Med β Cryomodule 2, Cavity Position 3, Lorentz Transfer Function (5MV/m CW)

- ✓ Time domain piezo tuner transfer function(pulse mode, impulse response)




S1G_A2

Cavity Turn on/ without beam



1. RF Cables Calibration.
   - Time Domain Reflectometer (TDR) cables check
   - Directional Couplers / Circulators: get calibration data.
   - Calibrate RF power measurement cables with attenuators at 352MHz/704MHz
   - Make RF calibration summary table

2. Technical Interlock / Sensors.
   - Check the sensors (e-, arc detector, water flow, temperature, etc)
   - Set the hardware interlock thresholds
   - Check the interlock

3. RF source / Waveguides / LLRF.
   - Klystron / LLRF check on the load
   - Waveguides visual check
   - System check / RF leak check at low power

4. Cooldown to 2K.

5. Cavity Spectra measurements.
   - Measure the fundamental mode spectra
   - Measure the cavities HOMs spectra and Q_{load}
   - Calibrate the cold RF cables at 2K

6. Cavity Tuners Test.
   - Test the cavities step-motor frequency tuners and record the motor tuner to cavity detuning transfer function.
   - Tune the cavities to the 352MHz/704.42MHz using the Network Analyzer

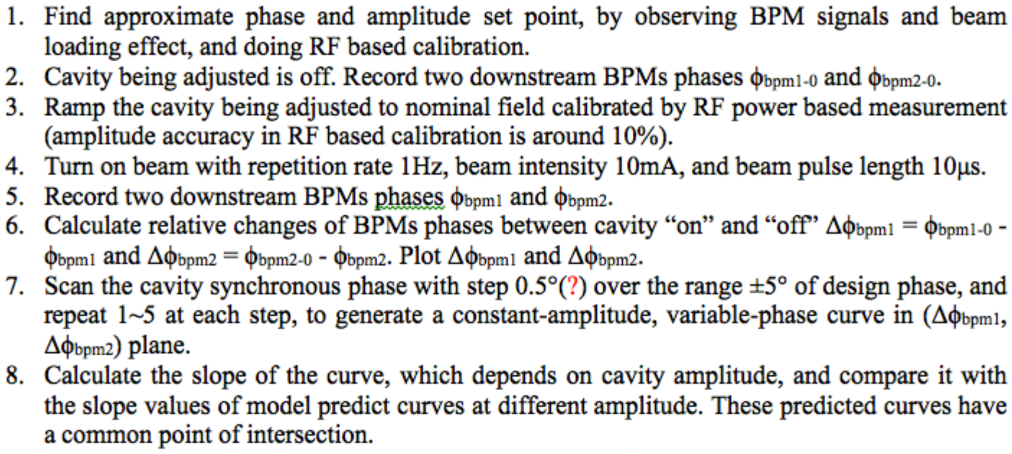
7. Cavities On Resonance.
   - Cavities fine-tuning to the 352.21MHz/704.42MHz by using piezo tuner
   - Q_{load}, K_t calibration ($E_{acc}=k_t\times(P_{trans})^{1/2}$)

8. Input RF Couplers and Cavities Conditioning.
   - Find the cavities/couplers limits at low repetition rate
   - Run the standard cavity/coupler conditioning program (the follow is an example at Desy):
     20, 50, 100, 200 µs pulse lengths up to 1MW (minimum 700kW),
     300, 400 µs up to 330 kW,
     500 µs + 100, 200, 400, 800 µs flat top pulse up to 250 kW,
     Cavities high peak power (HPP) test is part of the conditioning (automatic),

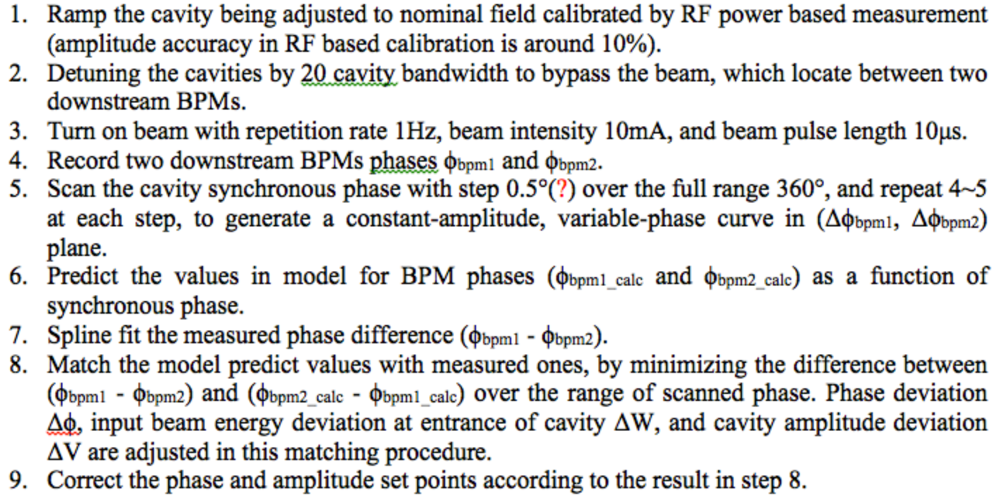
9. Cavity Gradient Ramp up.
   - Load feed forward tables for low gradient operation. Simulated beam with synchronous phase is included in the feed-forward signals, and preliminary injection time is calculated according to measured Q_{Load}.
   - Modulate the phase of RF power during filling time to track the cavity resonance frequency, in order to minimize RF power required compensating detuning effect during filling time.
   - Adjust motor tuner and adjust injection time to obtain a constant cavity field at low gradient operation where Lorentz force detuning is small. The adjusted injection time is recorded and employed in feedforward tables and feedback setpoints.
   - Set a proper pre-detuning via motor tuner to compensate synchronous phase operation and to minimize the Lorentz force detuning effect at nominal gradient. The Lorentz force detuning is measured in advance or predict by models.
   - Scale up the feed forward tables to reach higher gradient.
   - Raise gradient slowly.
   - When rising close to nominal gradient, update feedforward table by measuring dynamic cavity detuning in previous pulses from forward, reflected, and transmitted powers. In such a way, Lorentz force detuning and pre-detuning expect to be compensated.
   - Optimize the pre-detuning to reduce the RF power.
   - Apply feedback once the open loop response is close to the desired closed loop response.
   - Increase gain to nominal.
   - Optimize feedback parameters for minimum residual amplitude and phase fluctuation during flat-top.

10. Cavity Quench Threshold Identification.
    - Cavity maximum gradient measurement at low repetition rate
    - Cavity maximum accelerating gradient measurement at nominal repetition rate with cryo losses (Q_o) and radiation measurements
    - Radiation / Dark Current measurements, if needed.
    - Quench detection can be made by detecting Q_{load} , since there is sharp drop in Q_{load} when quench occurring. Fast quench handling can be therefore made in next pulse by reducing or shut off the RF power.
    - Detailed and high-resolution quench level identification is essential to work close to limitation. Firstly, ramp up the cavity gradient with 1 MV/m until a quench is detected and RF safely turned off. After a brief cryogenic recovery time, a second ramp-up is performed using smaller gradient increments (0.1 MV/m). The two measurements are correlated and archived, along with the forward, reflected and probe waveforms leading to the two quenches. Near-quench and safe-operation thresholds are calculated for every cavity as a function of their measured

Cavity Turn on/ with beam

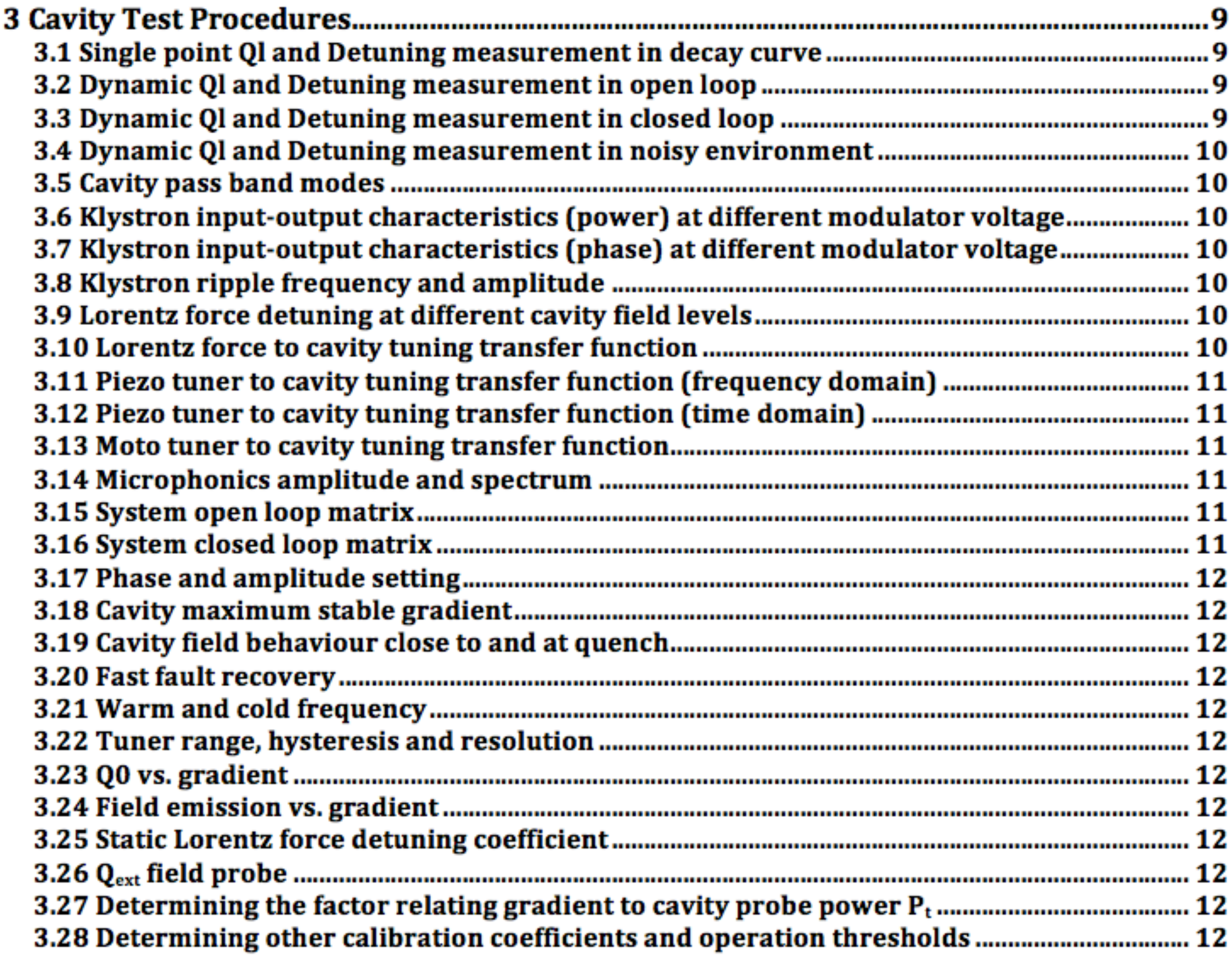


1. Find approximate phase and amplitude set point, by observing BPM signals and beam loading effect, and doing RF based calibration.
2. Cavity being adjusted is off. Record two downstream BPMs phases $\phi_{bpm1\text{-}0}$ and $\phi_{bpm2\text{-}0}$.
3. Ramp the cavity being adjusted to nominal field calibrated by RF power based measurement (amplitude accuracy in RF based calibration is around 10%).
4. Turn on beam with repetition rate 1Hz, beam intensity 10mA, and beam pulse length 10µs.
5. Record two downstream BPMs phases ϕ_{bpm1} and ϕ_{bpm2}.
6. Calculate relative changes of BPMs phases between cavity "on" and "off" $\Delta\phi_{bpm1} = \phi_{bpm1\text{-}0} - \phi_{bpm1}$ and $\Delta\phi_{bpm2} = \phi_{bpm2\text{-}0} - \phi_{bpm2}$. Plot $\Delta\phi_{bpm1}$ and $\Delta\phi_{bpm2}$.
7. Scan the cavity synchronous phase with step 0.5°(?) over the range ±5° of design phase, and repeat 1~5 at each step, to generate a constant-amplitude, variable-phase curve in ($\Delta\phi_{bpm1}$, $\Delta\phi_{bpm2}$) plane.
8. Calculate the slope of the curve, which depends on cavity amplitude, and compare it with the slope values of model predict curves at different amplitude. These predicted curves have a common point of intersection.
9. Use some fitting algorithm to determine best-fit amplitude.
10. Having determined proper amplitude, it is now able in mode function relating $\Delta\phi_{bpm1}$ and $\Delta\phi_{bpm2}$ to phase deviation $\Delta\phi$ and e entrance of cavity with respect to nominal value. $\Delta\phi$ and ΔW can



1. Ramp the cavity being adjusted to nominal field calibrated by RF power based measurement (amplitude accuracy in RF based calibration is around 10%).
2. Detuning the cavities by 20 cavity bandwidth to bypass the beam, which locate between two downstream BPMs.
3. Turn on beam with repetition rate 1Hz, beam intensity 10mA, and beam pulse length 10µs.
4. Record two downstream BPMs phases ϕ_{bpm1} and ϕ_{bpm2}.
5. Scan the cavity synchronous phase with step 0.5°(?) over the full range 360°, and repeat 4~5 at each step, to generate a constant-amplitude, variable-phase curve in ($\Delta\phi_{bpm1}$, $\Delta\phi_{bpm2}$) plane.
6. Predict the values in model for BPM phases (ϕ_{bpm1_calc} and ϕ_{bpm2_calc}) as a function of synchronous phase.
7. Spline fit the measured phase difference ($\phi_{bpm1} - \phi_{bpm2}$).
8. Match the model predict values with measured ones, by minimizing the difference between ($\phi_{bpm1} - \phi_{bpm2}$) and ($\phi_{bpm2\_calc} - \phi_{bpm1\_calc}$) over the range of scanned phase. Phase deviation $\Delta\phi$, input beam energy deviation at entrance of cavity ΔW, and cavity amplitude deviation ΔV are adjusted in this matching procedure.
9. Correct the phase and amplitude set points according to the result in step 8.

Cavity tests



Thanks!