ESS Cavity Tuning

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LLRF-Beam Dynamic Workshop

Outline

- ✓ Cavity tuning at ESS
  - Backgroud
  - Challenges at ESS
  - Advantages at ESS
- ✓ Roughly track back on phase scan at SNS
- ✓ Some thought to discussion
  - Definition of static error, phase drift
  - Phase drift in phase reference line

Cavity Turn on Procedures…

Procedures for ESS Superconducting Cavities Turn on

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Version 2.2(not complete)

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Background

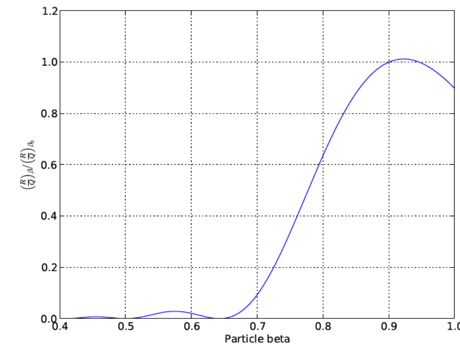
- ✓ Cavity tuning at ESS is examined more from RF perspective, "Turn on procedures"
- ✓ The start point is to solve the problem **"When the cavity is installed in tunnel at ESS, how to turn on RF power to reach required gradient, and what to be done when the beam comes?"**
- ✓ Face up to challenges at ESS:
  - Cavity control challenges
  - Cavity operation challenges
  - Cavity test challenges

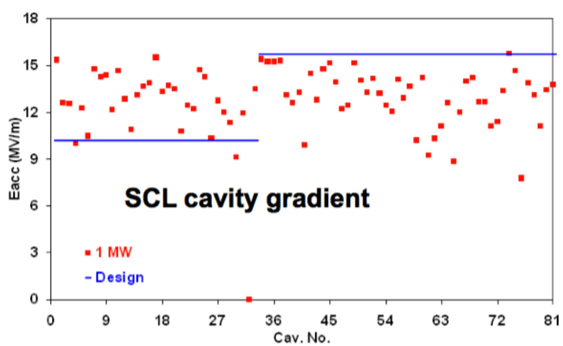
Cavity Control Challenges

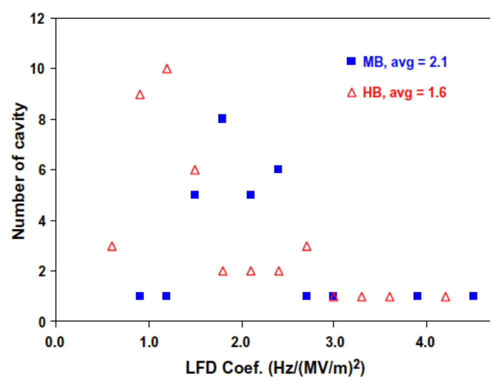
- **Higher Stability requirement**
- **Long pulse(~3.5ms RF pulses)**
  - Much longer Lorentz force detuning dynamics during pulse, might not be able to get compensated by traditional way driving the piezo with a simple half-cycle sinusoid impulse
  - Klystron output droop and ripple might be bigger due to long RF pulse
- **High intensity (62.5mA)**
  - 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 (~20MV/m)**
  - 44MV/m maximum surface field(Accelerating gradient 19.9MV/m)
- **High beam power(5MW)**
  - 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(have not ever used in any accelerator)**
  - 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

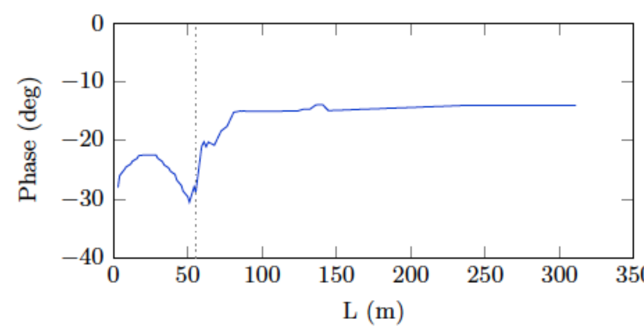
Cavity Operation Challenge

- ✓ 155 Cavities….
- ✓ Cavity gradient spread(could be up to 50%)
- ✓ Dynamic detuning spread
- ✓ Q load value spread >20%
- ✓ Beam velocity induced R/Q, Vc spread
- ✓ Synchronous phase









Cavity RF/LLRF Test Challenges

- ✓ 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.

- ✓ Take full advantages at ESS
  - High performance hardware
  - High precision RF measurement for cavity parameters: Ql, dynamic detuning, R/Q, phase, and amplitude
  - Opportunity to get first hand high quality data and sophisticated model to figure out RF & cavity dynamics

- ✓ Identify optimum procedures and develop together with ESS partners

- ✓ identify methodology and systematic way to really address challenges

Advantage of High Performance Hardware (Both LLRF&BPM)

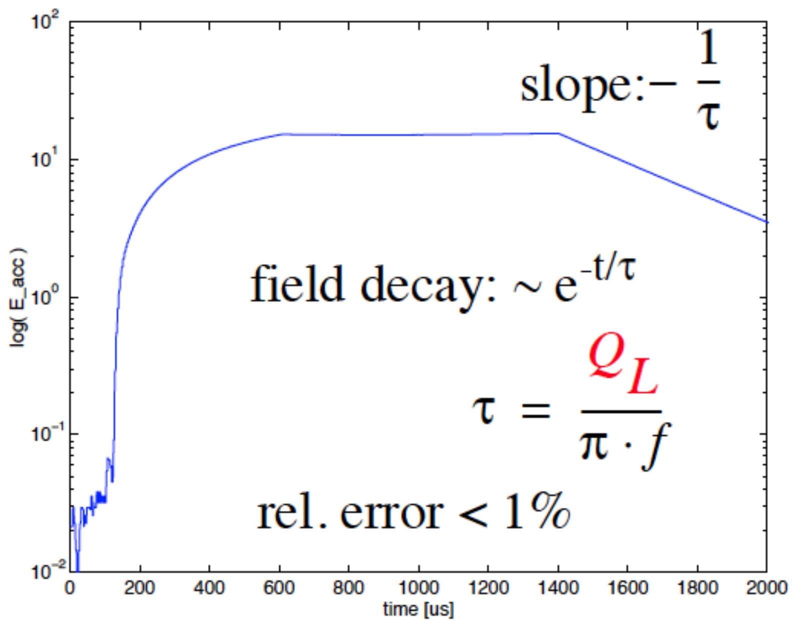
- ✓ **Low Latency in FPGA (~300ns), compared with 5 us in old times with DSP…**
- ✓ **Powerful hardware performance: 10 input channel**
- ✓ **~1000 times bigger memory in FPGA,**
- ✓ **faster CPU, communication,**
- ✓ **16bit ADC, higher SNR>70dB**
- ✓ **Memory resolution able to <10ns**

Take full advantage at ESS

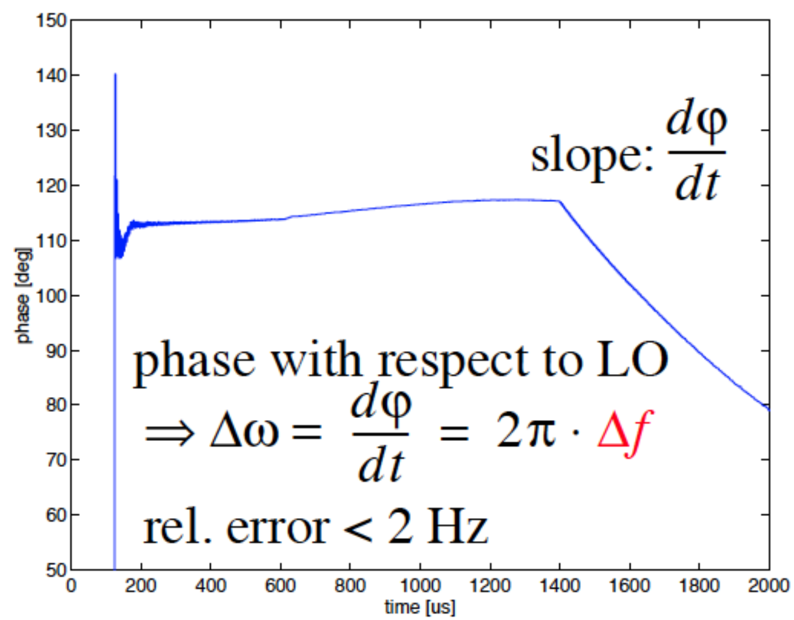
- ✓ High precision RF measurement for basic cavity parameters
  - Ql
  - Dynamic detuning
  - R/Q
  - Phase
  - Amplitude

High precision RF measurement: Ql, detuning

S. Simrock

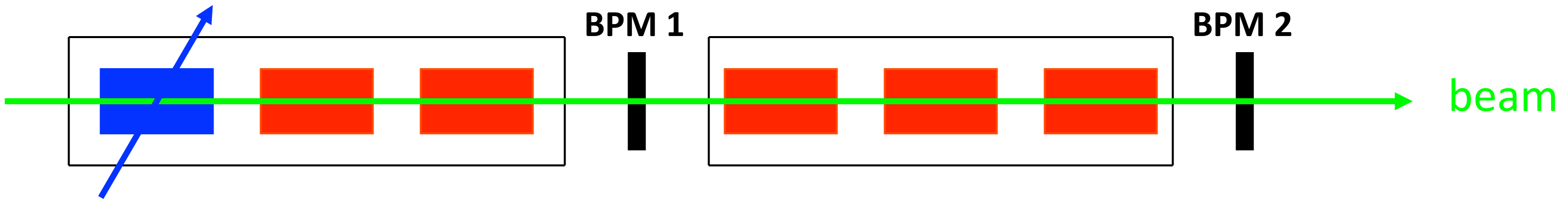


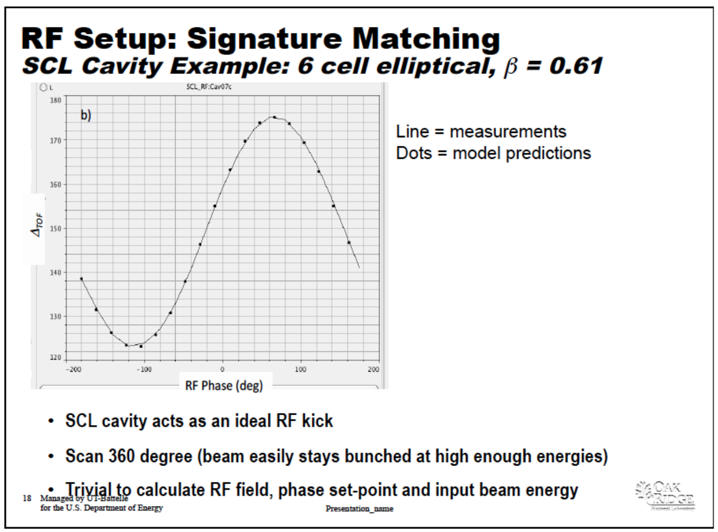
Loaded Q

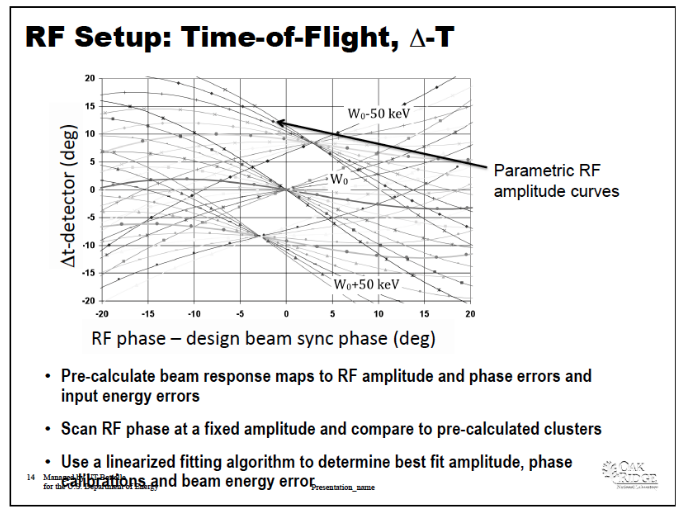


Detuning

Beam based calibration: Phase&Amplitude





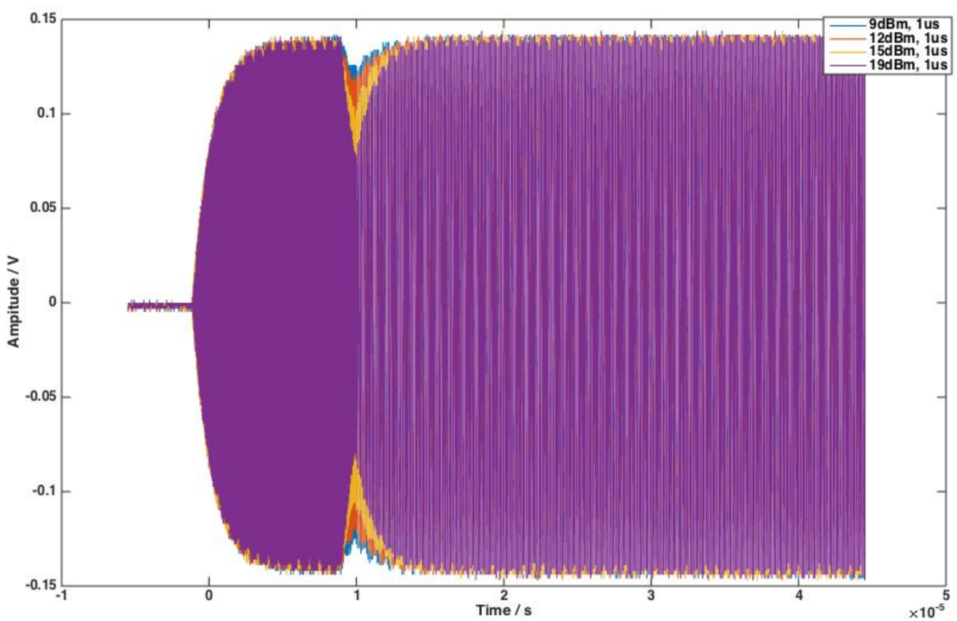


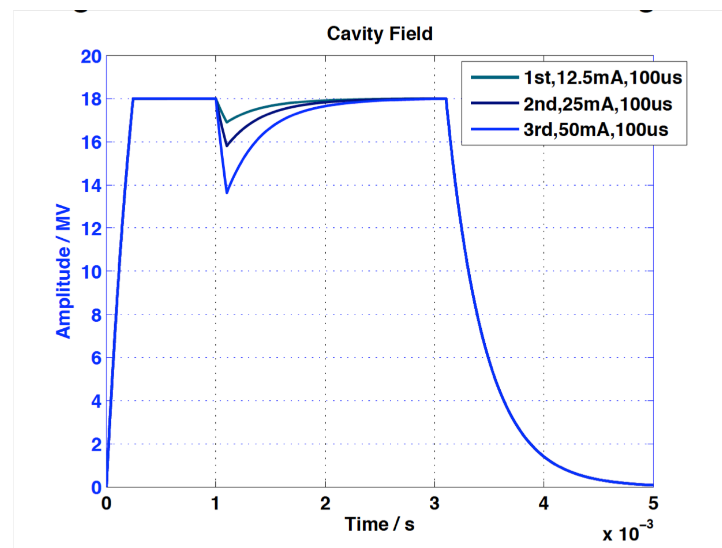
$$\Delta W = qE_0TL\cos\phi_0,$$

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

High precision RF measurement: R/Q Calibration

$$V_{\max} \approx \frac{\omega_0}{4}(R/Q)T_B \cdot I \qquad (6)$$





Take full advantage at ESS

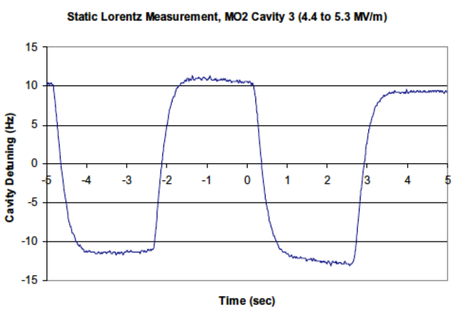
– to get first hand high quality data (to get what we want)

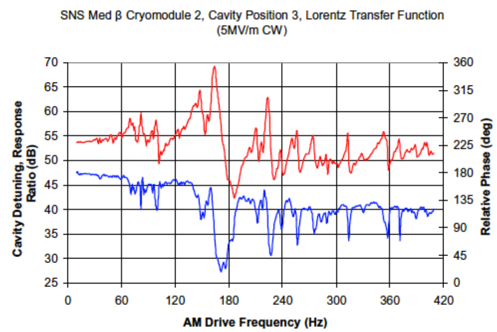
– and sophisticated model to figure out RF & cavity dynamics

Get data as we required

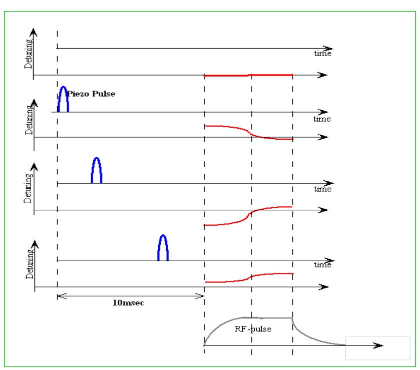
- ✓ With high performance hardware, we are able to carry out elaborate experimentation and obtain required data for particular purpose

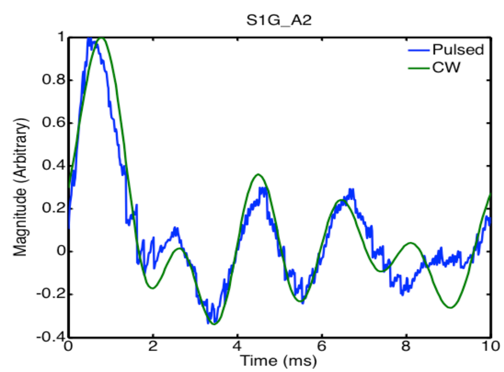
- ✓ Example: Lorentz Force Detuning Compensation
  - Static LFD coefficients



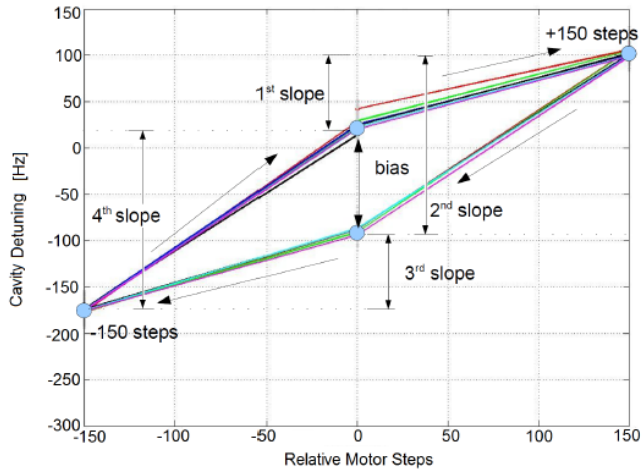


- ✓ Time domain piezo tuner transfer function(pulse mode, impulse response)

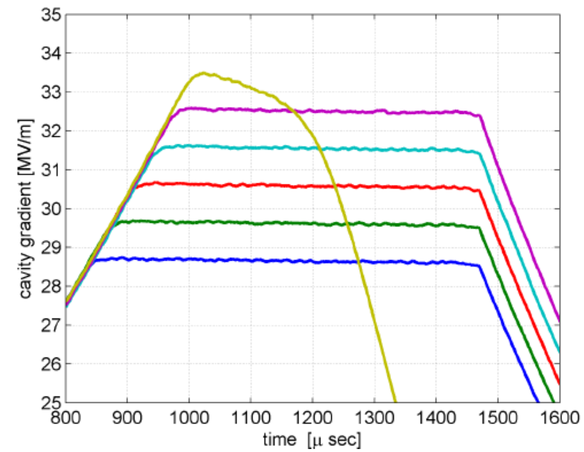




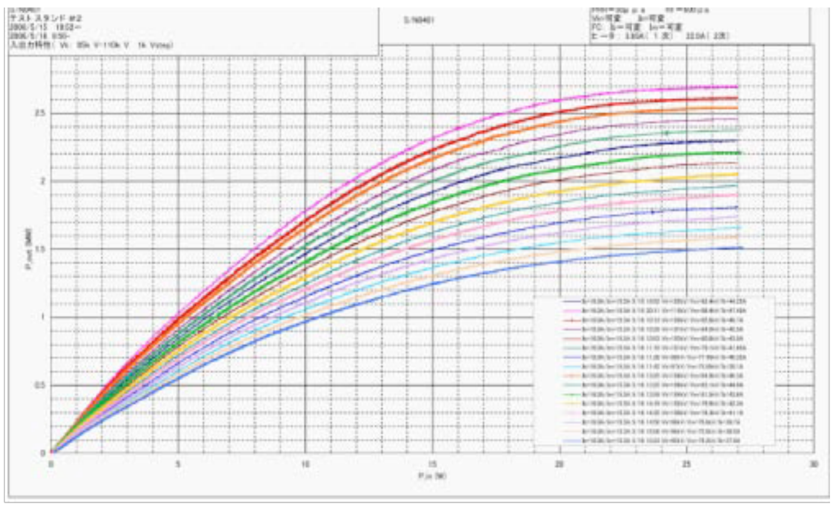
Well-Recorded data in high details



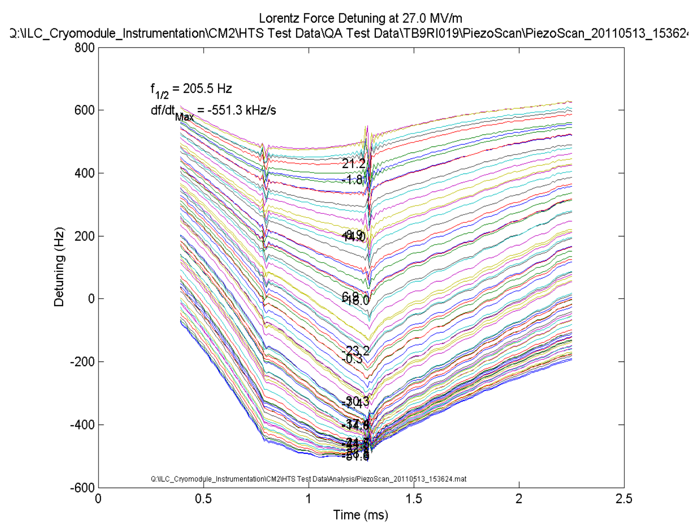
Motor tuner transfer function/DESY



Quench limitation identification/DESY



Klystron input-output characteristics/JPARC



Lorentz force detuning/Fermilab

✓ Roughly back-trace on SNS phase & amplitude setting

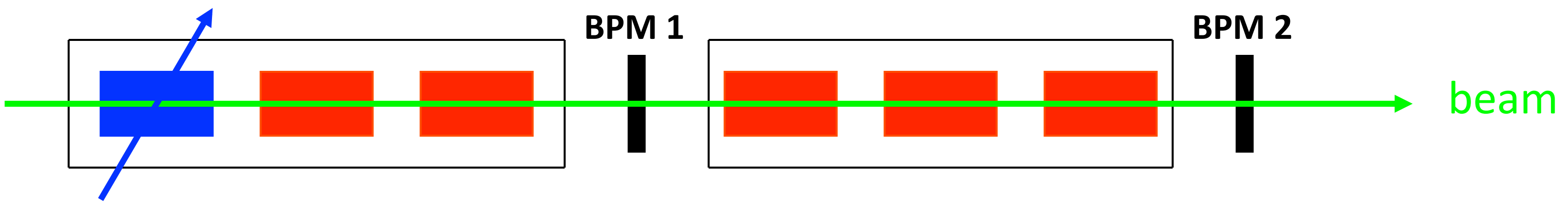
Early stage

Table 1: Overview of cavity phase and amplitude setting methods used at SNS

	Warm Linac			Superconducting Linac		
	Beam Based Calibration			Beam Based Calibration		RF based Calibration
	Energy degrader (only for DTL)	Delt-T	Phase-scan signature	Phase-scan signature	Drift Beam	
Amplitude	1.7% (at most) differ from Delt-T results[7]		Varied 0~5% with Delt-T results	±2.4%[1]	±4%(better results after precise calibration for BCM)[1]	±5%[1]
Phase	1.5 °(at most) differ from Delt-T results[7]		Varied 0~11° with Delt-T results	±1°	±1°	
Beam pulse	<50us[5]	<50us	<50us[8]	~20us[2] 5~20us[3]	>50us[4]	N/A
Beam Current	<20mA[5]		>5mA	<20mA[2] 5mA is threshold*[6]	<20mA[4]	N/A
Repetition rates	1Hz	1Hz	1Hz	1Hz	1Hz	1Hz
Error Source		Beam parameters	BPM Calibration Beam parameters Beam loading in unpowered cavities	BPM Calibration Beam parameters Beam loading in unpowered cavities	BCM Calibration Beam Parameters LLRF noise Cavity detuning Passband modes	Measurement errors Cavity parameters errors

Improvements to phase scan method

Slide from M. Plum (Beam commissioning workshop at ESS. April 8~9, 2014)

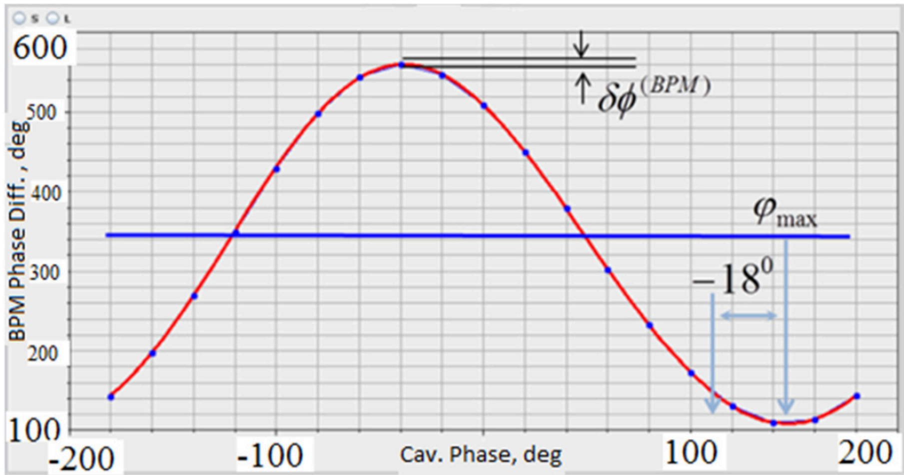


- ✓ When we first commissioned the SCL we turned off the RF to the cavities downstream of the cavity whose phase was being scanned. It took about 15 minutes to turn on the next cavity and move on.
- ✓ Now we just blank the RF at 1 Hz (59 RF pulses on, 1 pulse off) and that can be turned on or off in about 1 second
- ✓ We use low peak currents (~5 mA) and short pulses (~3 us) to minimize the cavity excitations and beam loading
- ✓ In the first years of routine operations the SCL phase scans took about 12 hours. Today they are automated and take about 40 minutes.

- ✓ Cavity amplitudes set to maximum stable gradients – much different than design gradients

Linac 14 paper from A. Shishlo(SNS)

- ✓ Setting phases of all RF cavities.



- ✓ The amplitudes of the cavities (field gradients) are not a subject of tuning. These values are defined by the SCL group to be as high as possible and, at the same time, to provide a stable operation

✓ Energy calibration:

- First, all cavities are scanned and the phases are setup based on un-calibrated pairs of BPMs
- Second, transport the beam coming out of SCL into the SNS ring, and use the ring as an energy measuring device.
- Finally, use the model to analyse the scan data for each cavity using all available BPMs

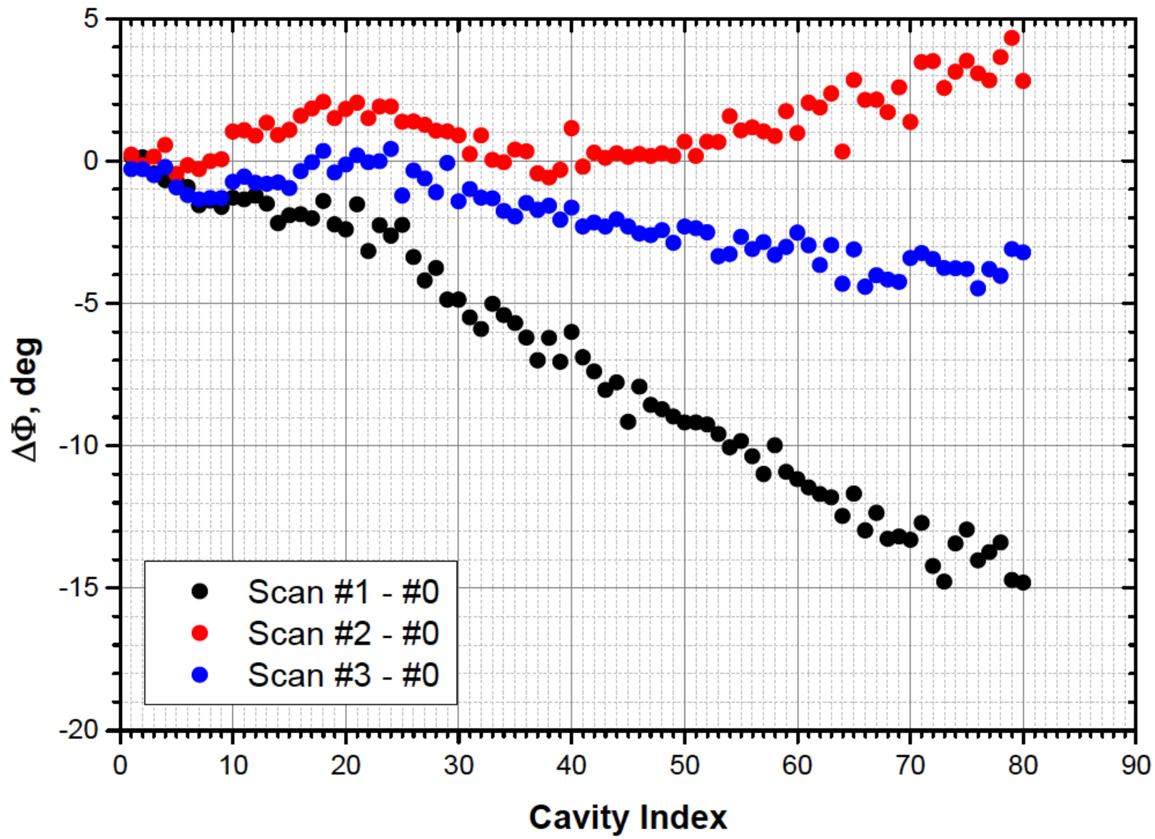
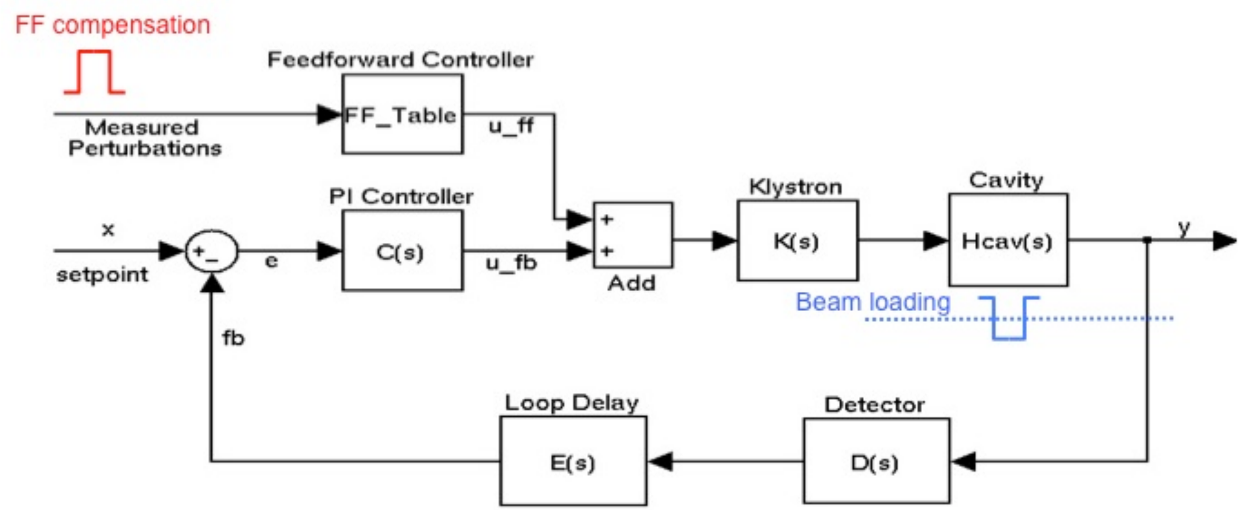


Figure 3: The SCL cavitiy phase differences for four consecutive phase scans.

- ✓ It seems static error can be big, and flexible to change, if we define it as deviation to design value

- ✓ Some general thought for discussion:
  - Distinguish static setting error and thermal drift
    - Two setpoints, one for amplitude A,
    - The other one , for relative phase $\Delta\varphi=\varphi_{RF,\,cav}-\varphi_{ref}$



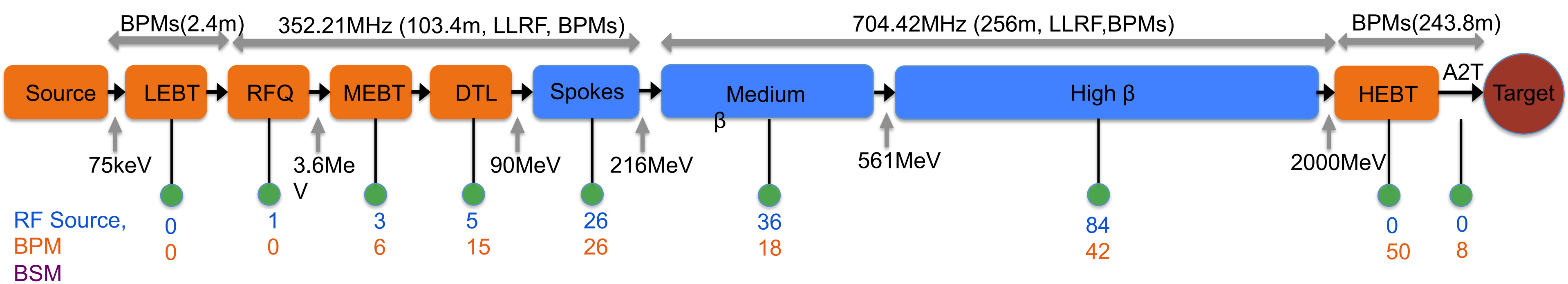
- Static setting error definition: absolute deviation from design value, (for example, for static error, if design value is 14 deg, then the value in set piont is 15 deg or 16 deg)

- Or, relative adjustable resolution (for example, if we want to set 14 deg, then 1 deg error means, we might have 14±1 deg, but it is OK if the absolute value seen by beam is 17±1deg.)

- There no absolute value, and the design value is changing during operation…

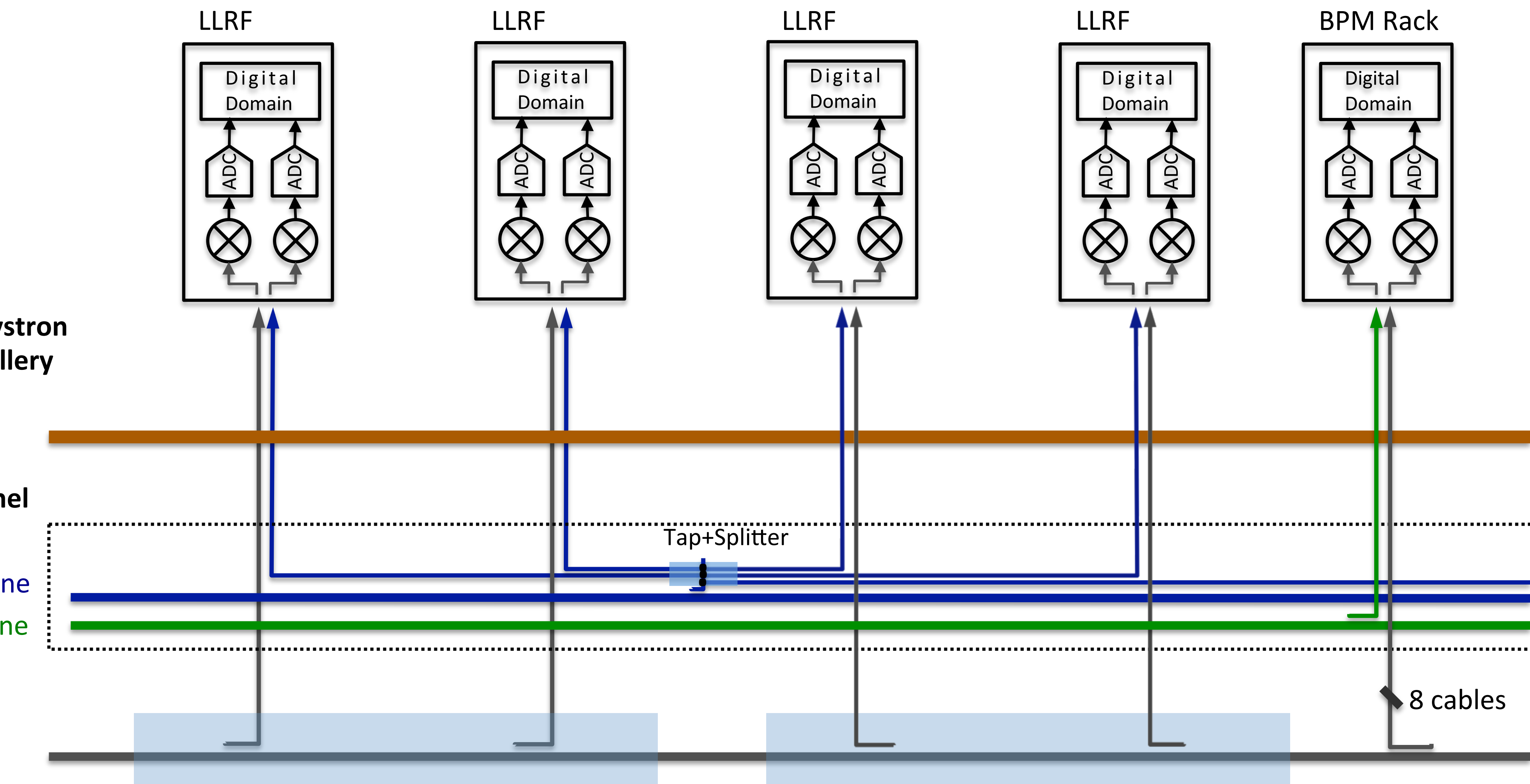
Phase reference distribution at ESS

- ✓ For LLRF, BPMs, along the whole tunnel
- ✓ Stability requirement 0.1° for short term(during pulse), 1° for long term(hours to days)
- ✓ Drift ~±10° for 704MHz section (tunnel temperature ±2.5°C,only rigid line, not considering RF components drift). Drift ~20° for 704MHz section + HEBT.
- ✓ Drift ~±2° for 352MHz section.



62.5mA
2.86ms
14Hz
5MW

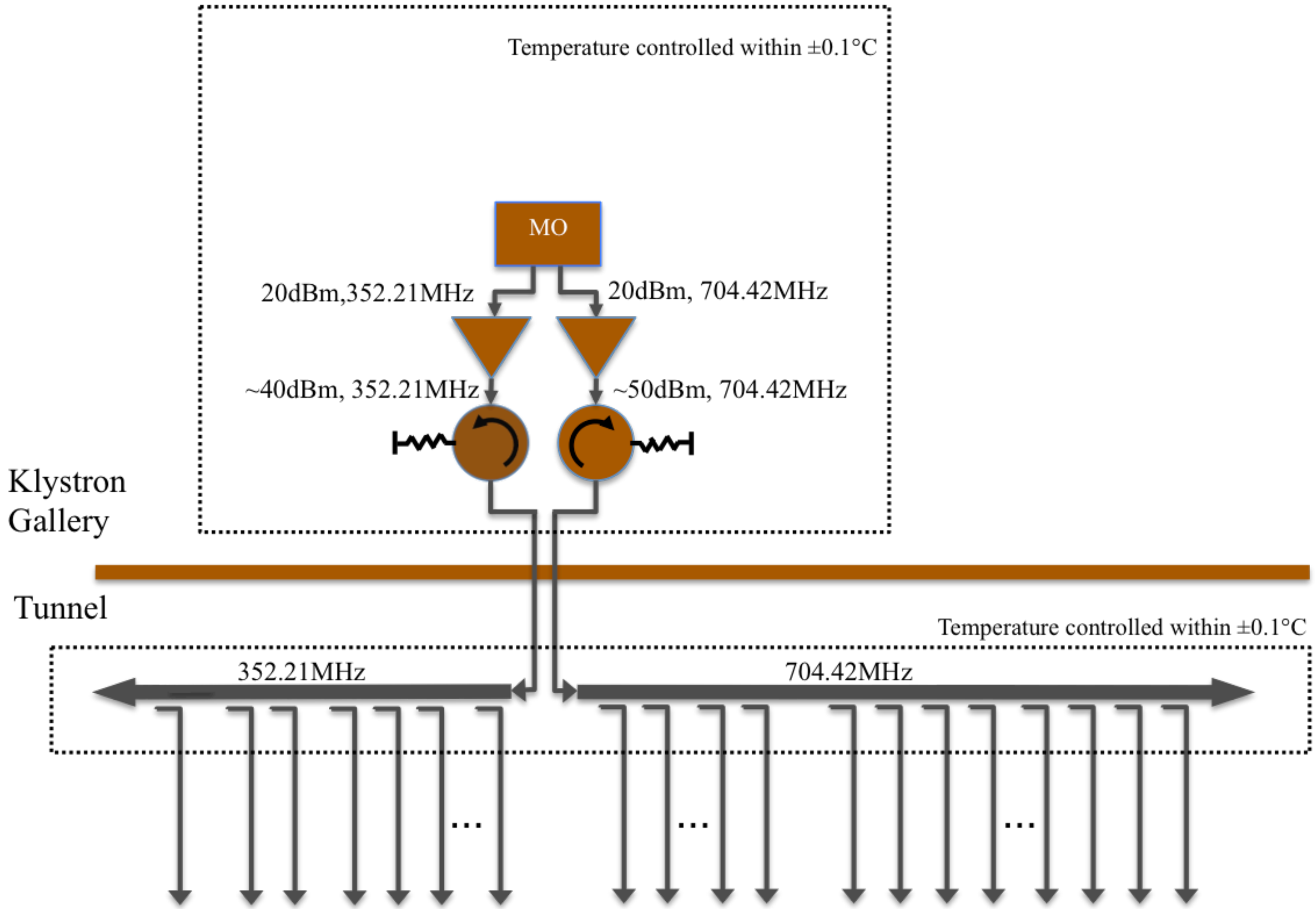
More drift in local distribution(from Tunnel to Gallery)



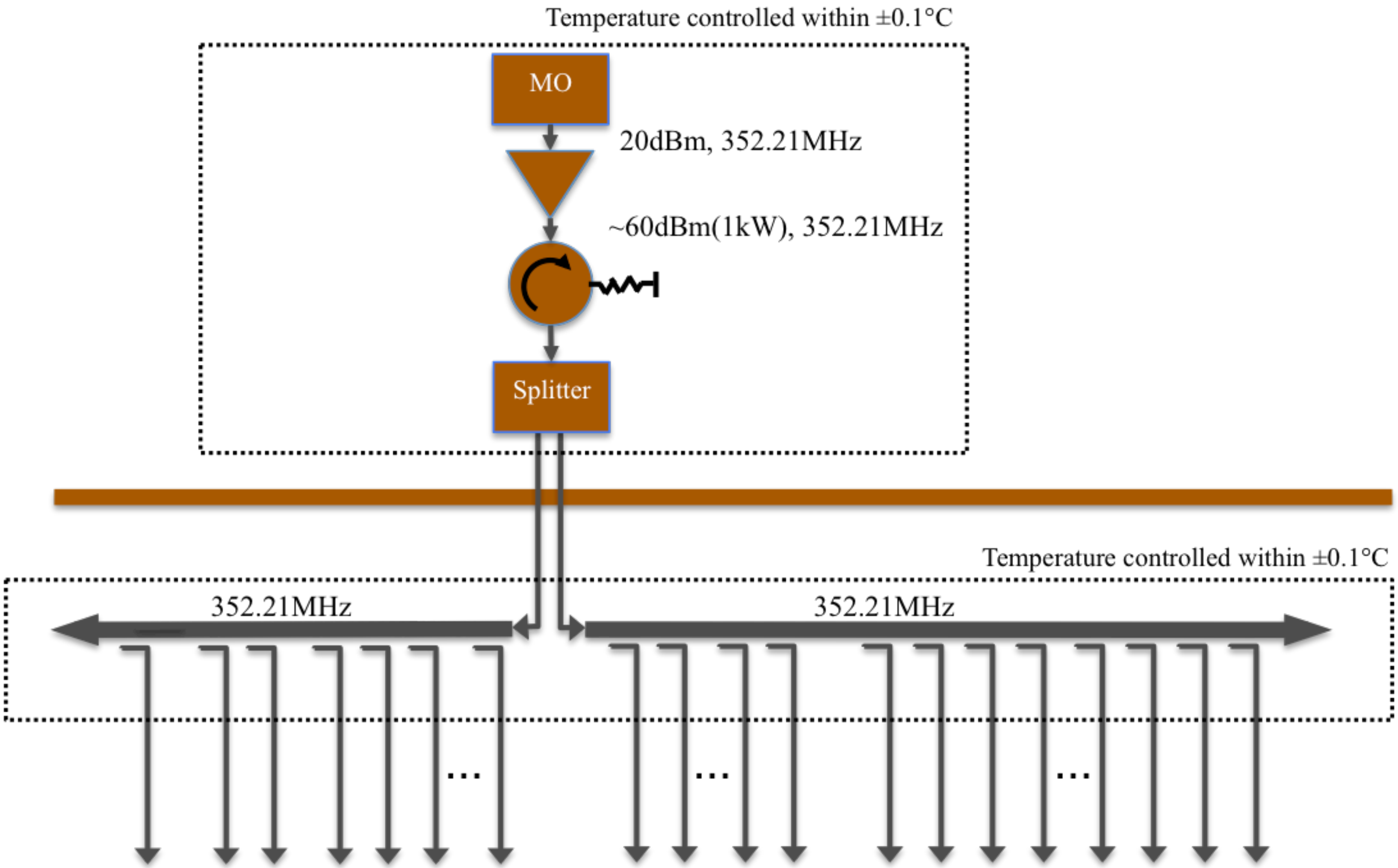
Cryo-module1(Spoke), Length, 2860mm, from vacuum valve to vacuum valve, cavity power coupler to coupler distance 1129mm.

Vacuum valve to first BPM 679.48mm, to second BPM 1134.47mm(to be confirmed)

2 line or 1 line for Phase reference distribution



Note: 1. 15dBm at each tap point for LLRF, BPMs, and BSMs.
2. For BPMs, frequency divider or multiplier is used to generate different harmonics, opposite with cavity RF signal.


Temperature controlled within ±0.1°C
MO
20dBm, 352.21MHz
~60dBm(1kW), 352.21MHz
Splitter
Temperature controlled within ±0.1°C
352.21MHz
352.21MHz
...
...
...

EUROPEAN
SPALLATION
SOURCE

Thanks!