Status and preliminary Test of LLRF Control System of Cryomodules for the MESA

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MAINZ Energy-Recovering Superconducting Accelerator

MESA two operation modes:

- **External Beam (EB) mode**: polarized beam 155MeV & 150μA
- **Energy Recovering (ER) mode**: unpolarized beam 105MeV & 1mA
- High field amplitude stability 0.01%
- High field phase stability 0.01°

MicroTCA.4 based LLRF system developed by DESY
MicroTCA.4 based LLRF system includes Phase & amplitude control and Frequency detuning control.

Concept of LLRF System

![Diagram of TESLA 9-cell SC cavity with power coupler, Saclay II tuner, and HOM coupler.

Solid State Power Amplifier

Power coupler

Circulator

SSPA

Up conversion

DAC

Digital controller

ADC

Pick-up antenna

Analog process

Up conversion

Tuner controller

Down conversion

Digital process

Δf

ΔA

Δφ

Δf

ΔA

Δφ
Hardware of LLRF System

Hardware from MicroTCA Technology Lab & Partners
Firmware from MSK, DESY

Front

Back

MCH  CPU
FMC20+2*MD22
SIS8300L2
x2timer

Digital process

DWC8VM1

Analog process
Test Bench at HIM

Helmholtz-Institut Mainz (HIM) test bunker

Outside the bunker
Existing phase lock loop (PLL) System $\rightarrow$ resonance frequency

For more information about the PLL system, please check S. Thomas, Master thesis "Aufbau einer Hochfrequenzregelung zur Vermessung der supraleitenden MESA Beschleuniger-Module", Johannes Gutenberg-Universität Mainz, 2018
LLRF Test without Frequency Detuning Control

➔ LLRF + PLL nested control loop

PLL: Frequency modulation
→ Resonance frequency control loop
LLRF: Amplitude modulation
→ Amplitude & Phase control loop

Master Oscillator
Generator
Local oscillator generator
PLL

→ Forward signal
Cavity
Pick up signal

Master Oscillator
Generator
Local oscillator generator
PLL

→ Forward signal
Cavity
Pick up signal

→ Keysight Spectrum Analyzer
→ RMS amplitude stability
→ RMS phase stability

Master Oscillator
Generator
Local oscillator generator
PLL

→ Forward signal
Cavity
Pick up signal
LLRF Test without Frequency Detuning Control

Accelerating Field during the LLRF Test

PLL + LLRF

Instability

LLRF

07-Jun-2019 14:20:00

07-Jun-2019 14:40:00
RMS amplitude stability (LLRF: Feed forward + Feed back P=1.4)

\[
\frac{1}{\sqrt{2}} \cdot \frac{Amp_{\text{Max}} - Amp_{\text{Min}}}{2 Amp_{\text{Avg}}} \cdot 100\% = 3.56\%
\]
**RMS phase stability** (LLRF: Feed forward + Feed back P=1.4)  

1.06°

---

**Equation (1):**

\[
A = \text{Integrated phase noise power from 10Hz to 1MHz (dBc)}
\]

\[
\text{RMS phase stability (degrees)} = \frac{180}{\pi} \cdot \sqrt{2} \cdot 10^{A/10} \quad (1)
\]

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Eq. (1) is from “Phase Noise Measurement Methods and Techniques - Keysight”
LLRF Control Loop Test

LLRF: Feed forward + Feed back (P=1.4)

- RMS amplitude stability: 3.56%
- RMS phase stability: 1.06°

Amplitude and phase of the pick up antenna signal

Sample frequency $1.3\text{GHz}/24\times3=162.5\text{MHz}$

Instability frequency $\approx 5\text{kHz}$

Caused by 50V DC power supply for SSPA with the phase jump 5kHz and 1°, a better power supply is ordered.
Instability caused by varied resonance frequency due to the helium pressure fluctuations

Controller parameter optimization is required!
Frequency detuning control needs to be implemented!
Stepper Motor Test

MicroTCA.4 based stepper motor system → Frequency detuning control

MESA
- Normal conducting cavity → Crouzet stepper motor

- SC cavity → Saclay Tuner II with Phytron VSS-52 stepper motor & piezo tuners

Is also used for MAMI (Mainzer Mikrotron)

Calibration step is in accordance with the existing system.

≈ 0.7Hz/step

MicroTCA.4 based stepper motor system (FMC20+2*MD22)

drive

?
Conclusion & Outlook

**2018 – June 2019**

- SIMULINK Modeling of RF cavity control
- Setup of the MicroTCA system & firmware adaption
- LLRF system test for MESA cryomodules
- Stepper motors test for both MESA NC & SC cavities

**Next steps**

- Controller parameter optimization for MTCA system
- Cavity system identification for MTCA system by Matlab/SIMULINK
- MTCA system integration of the stepper motor control and piezo control for the frequency detuning control
THANKS

to colleagues from MESA for support

to colleagues from DESY for support

to you for YOUR ATTENTION!
Backup slides
Local Oscillator Generator

Master Oscillator

- LO => Down Conversion
- CLK => ADC Sampling
- REF => Up Conversion

R&S Signal Generator SME03 + Keysight PXA Signal Analyzer

- RMS phase noise: 198 fs
- RMS amplitude stability:
  0.005% (30 sec)
  0.028% (5 min)
LLRF Control Loop Test

**LLRF**: Feed forward + Feed back (P=1.4)

- RMS amplitude stability: 3.56%
- RMS phase stability: 1.06°

Far beyond the MESA requirements!

Sample frequency $1.3\text{GHz}/24*3=162.5\text{MHz}$

Instability frequency $162.5\text{MHz} / (16384*2) \approx 5\text{kHz}$

Caused by 50V DC power supply for SSPA with the phase jump 5kHz and 1°

Half period of the instability
Existing phase lock loop (PLL) System $\rightarrow$ resonance frequency

**Frequency modulation**

1. **Generator**
   - Ext In: 1 Vp-P signal
   - Max 5 Vrms
   - Max 10 Vpk

2. **Oszi**
   - Voltage Amp + 43 dB

3. **Det**
   - Low pass filter

4. **SSPA**
   - Cable: -2 dB
   - IF
   - LO
   - LO+RF max 20 dB

5. **Cavity**
   - +75 dB
   - -50 dB
   - -3 dB

6. **Pick up signal**
   - -0.7 dB
   - -10 dB
   - -0.2 dB
   - -0.7 dB
   - -10 dB
   - -3 dB
   - -3 dB
   - -10 dB
   - -10 dB

7. **Spectrum analyzer**
   - -0.2 dB

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Jiaoni Bai, MTCA/ATCA Workshop for Research and Industry, Peking, 25.06.2019
PLL + LLRF Test

PLL+LLRF test result

- RMS phase noise: 1.54 degree
- RMS amplitude stability: 5.05%
Phytron VSS-52 stepper motor with full step (4K) ≈ 1.4Hz/step

Phytron VSS-52 stepper motor with half step (4K) ≈ 0.7Hz/step
Cryogenic System

Rückleitung 5°-Halle

Flussmessung

Subatmosphärischer Kompressor

1 bar Heizer

Abdampfen

16 mbar Heizer

LN₂ Geschirmte Leitung

LN₂

4.15 K LHe

LN₂ Dewar

He Dewar

N₂ Dewar

Ventilbox

Control valve

1.8K phase separator

Modul

LHe 1 bar

GHe 1 bar

GHe 16 mbar

LHe 1 4.4K

LN₂

2K System
### MESA Cryomodule

<table>
<thead>
<tr>
<th>Parameter</th>
<th>guaranteed</th>
</tr>
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<tbody>
<tr>
<td>$f_0(2K) / \text{GHz}$</td>
<td>$1.3 \pm 50 \text{kHz}$</td>
</tr>
<tr>
<td>$V_{\text{total}} / \text{MV}$</td>
<td>$\geq 25$</td>
</tr>
<tr>
<td>$Q_0$</td>
<td>$1.25 \times 10^{10}$</td>
</tr>
<tr>
<td>$P_{\text{FPC}} / \text{kW}$</td>
<td>$\geq 15$</td>
</tr>
<tr>
<td>$P_{\text{diss,stat}} / \text{W}$</td>
<td>$&lt; 15$</td>
</tr>
<tr>
<td>$P_{\text{diss,dyn}} / \text{W}$</td>
<td>$&lt; 25$</td>
</tr>
</tbody>
</table>

#### Modifications:
- XFEL tuner
- Thermal coupling of the HOM antenna
- 1.8 K distribution
- Valve box

T. Stengler et. al., „Modified Elbe Type Cryomodules for the Mainz Energy-Recovering Superconducting Accelerator MESA“, IPAC2016, WEPM009
CM2 (CAV009 & CAV010) limitation via radiation was likely caused by a damaged valve.

=> CM2 has been sent back to RI to be refurbished and will be delivered on September.

CM1 (CAV007 & CAV008) was tested recently. The Q0 jumps dramatically up and down. We will repeat the test next month.