RF COMMISSIONING AND PERFORMANCE IN THE CBETA ERL

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Abstract

The Cornell-BNL ERL Test Accelerator (CBETA) is a new multi-turn energy recovery linac currently being commissioned at Cornell University. It uses a superconducting main linac to accelerate electrons by 36 MeV and recover their energy. The energy recovery process is sensitive to fluctuations in the accelerating field of all cavities. In this paper, we outline our semi-automated RF commissioning procedure, which starts from automatic coarse tuning of the cavity all the way to adjusting the field control loops. We show some results of using these tools and describe the recent performance of the RF system during our ongoing commissioning phase.

INTRODUCTION

The Cornell-BNL ERL Test Accelerator (CBETA) [1] project currently being commissioned at Cornell University will be the first high-current multi-turn ERL employing Superconducting Radio Frequency (SRF) Linacs operating in CW. The SRF cavities are housed in two cryomodules, one for the injection system and the other is used to execute energy recovery. The injector cryomodule [2] consists of five 2-cell SRF cavities and is configured to provide a total energy gain of 6 MeV to the electron beam for injection into the CBETA return loop. It has been commissioned in multiple stages starting from 2009 and has reached a peak operating current of 70 mA in 2013 [3]. The main linac on the other hand will be used to execute energy recovery and incorporates six 7-cell SRF cavities [4] with a total design energy gain of 36 MeV. In this paper, we describe our progress in commissioning the Main Linac Cryomodule (MLC) for the energy recovery operation in CBETA along with our automated startup procedures.

In the next section, we describe our high level RF setup with results from initial testing of the Solid State Amplifiers and the circulators which provide RF power to the cavities. Then we describe the operating configuration of our cryogenic system which we have optimized for stable operations. After this, we describe our semi-automated RF commissioning procedure in detail and finally, we report our measurements during beam operations over the current commissioning phase.

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Figure 1: RF power arrangement for one main linac cavity. We inserted a waveguide short between the fundamental power coupler of the 7-cell SRF cavity and the 3-stub waveguide tuner during tests of the solid state amplifiers.

LINAC SUBSYSTEMS

The Main Linac Cryomodule (MLC) houses six 7-cell SRF cavities optimized for high-current operations with negligible beam loading. All six cavities are operated with a low bandwidth of ≈ 20 Hz and are powered by individual Solid State Amplifiers (SSA) from SigmaPhi connected through a circulator from AFT, directional coupler and a 3-stub waveguide tuner as shown in Fig. 1. There are two sets of high power RF components which are capable of 5 kW and 10 kW for stiffened [5] and un-stiffened cavities respectively. We first tested all these components to full power into a shortened waveguide before connecting them to the cavities. The initial tests revealed problems with both the RF amplifiers and the circulators.

Each SSA requires a power circulator for protection from a full reflection which is close to the typical operating condition. During initial tests we measured both the forward power from the amplifier and the power reflected back into the SSA from the circulator to verify isolation in the RF path. While operating at a few kW of RF power, we observed a sudden jump in the reflected power from ≈ 10 W to ≥ 200 W on all SSAs, which indicated a problem with the circulators. Eventually, we found that a plastic piece used to isolate an aluminum tuning screw from the water-cooled ferrite load had disintegrated during the initial tests, resulting in electrical breakdown and severe pitting in several areas of the load, along with loss of isolation characteristics of the circulator. After consulting with AFT, we discovered that the plastic piece installed on the end of the tuning screws had a much higher loss tangent than intended. These were eventually replaced and the load surfaces were cleaned after removing some broken pieces of ferrite. We then tested each circulator at low power with a network analyzer optimizing the isolation. A damaged internal RF cable also led to the failure of a single RF power module on a 5 kW SSA. Figure 2 shows the final measurements after necessary repairs indicating satisfactory performance of all high power RF components.
The cryogenic system of the MLC is based on the TESLA design. [6] Separate vessels house the six cavities and are supplied liquid Helium through chimneys by the 2 K - 2 phase pipe. The pressure exerted on the cavity walls influences the resonant frequency and needs to be regulated. Slow trends in this pressure give rise to very low frequency microphonics detuning ($\leq$ 1Hz) and tight cryogenic regulation is necessary during operations. When the RF system is off, two separate proportional integral loops control the Helium liquid level by varying the JT and the precool valves, while we maintain the vapour pressure by adjusting the speed of the external blowers. However actuation of these valves significantly contribute to peak microphonics detuning in the SRF cavities and this is suppressed by making these valves static. When the RF system is operating at low gradients, we set the pump skids to their minimum speed and adjust a bypass needle valve to apply some load to regulate the liquid level. In nominal conditions, the position of the JT valve is set to match the Helium boil off keeping the liquid level constant. One important indicator of cryogenic performance is the speed of the blowers shown in Fig. 3 which has been within acceptable limits with the two blowers connected to the HGRP never exceeding 50% of maximum speed for nominal energy gain of 36 MeV and both reaching 67.5% at the maximum gain of 53 MeV.

**RF COMMISSIONING AND PERFORMANCE**

Initial commissioning of the MLC after setting up the cryogenic and the high power RF systems, primarily involves tuning the cavities to resonance and setting up the Low Level Radio Frequency (LLRF) control system for optimum operations. In this section we document the procedures we follow to prepare the MLC for beam operations. While we have done the initial commissioning manually, most of these steps are automatically executed for routine operations using a dedicated sequencer capable of rudimentary error handling. Such automation has also been used elsewhere [8]. Repeating these procedures everyday accounts for drifts in the system and ensures stable operations.

**Step 1:** Cavity tuning is the first step towards setting up after cable calibration and we use stepper motor based slow tuners to obtain resonance at the clock frequency of 1299.9 MHz. We first use a network analyzer to tune the cavities within 10 kHz of the clock frequency at low field while we use the LLRF system in constant power mode (called Klystron Loop in the Cornell LLRF [7]) to fine tune the cavity to within a few Hz of resonance on average. During the tuning process, we maximize the field signal while using a forward power of 10 W which gives us the resonance position at an accelerating voltage just above 1.1 MV. The performance of the automatic coarse tuning algorithm based on decision tree approach is shown in Fig. 4. This step allows us to establish the field control loop at a low voltage of around 1 MV, which is a prerequisite for subsequent procedures.

**Step 2:** The Digital to Analog Converter (DAC) output used in the LLRF system to drive the vector modulator may have some offset due to manufacturing differences. This leads to some non-zero forward power being injected into...
the cavity even when the output is set to 0 leading to a
parasitic field appearing in the cavity when the feedback
loop is not active. To account for the offsets, both the
in-phase $I$ and the quadrature $Q$ components of the output
phaser are shifted by a programmable offset in the LLRF.
We measure parasitic forward power as a function of offset
as shown in Fig. 5 setting the optimum value at the position
of minimum power.

**Step 3:** The LLRF system implements various trips which
turn off RF power going into the cavity in case of a situation
which might damage the RF system. Setting the various
trip parameters is an important step in commissioning the
cavities. There are three categories of trip parameters which
we have to set. The SSA trip parameters set the threshold
for the maximum power reflected from the circulator into
the SSA. The power scale contains a calibration factor while
Max. power sets the scaled power threshold. The Power
trip parameters are thresholds on the maximum forward and
reflected power, while quench detection relies on a sudden
but sustained fractional decrease in reflected power. Finally,
we set the Field trip parameters which control the maximum
field tolerated by the system during normal operations.
The important trip parameters and their usage are listed in
Table 1.

**Step 4:** The phase rotation of the field signal due to the
cable length between the field probe and the control system
influences the stability of the constant field control loop
(called Cavity Loop in the Cornell LLRF) and also directly
affects measurement of the tuning angle $\phi_t \equiv \phi_{\text{field}} - \phi_{\text{drive}}$.
where $\phi_{\text{field}}$ is the phase difference between the field signal $\phi_{\text{field}}$
and the forward power signal $\phi_{\text{drive}}$. The detuning $\delta f$ of the
cavity is given by,

$$\delta f = \frac{f_{\text{drive}}}{2Q_L} \tan \phi_t,$$

where $Q_L$ is the loaded quality factor of the cavity, $f_{\text{drive}}$
is the clock frequency of the RF system. From Eq. 1 we can
conclude that $\delta f = 0 \implies \phi_t = 0$, and this is used to adjust
the field rotation offset. We first set the field rotation after
manual tuning done in step 1 so that measured tuning angle
approximately equals zero when the cavity is in tune. This
gives us the rotation value correct to 1-2 degrees. We then
observe the average forward power required to maintain a
stable field in the cavity (Cavity Loop) as a function of the
tuning angle $\phi_t$ set point of the resonance control feedback
loop. The position of minimum forward power corresponds
to a perfectly tuned cavity, and the phase rotation is adjusted
accordingly.

**Step 5:** Microphonics poses a major constraint on field
stability for the MLC cavities which we operate with high
$Q_L$ as noted in the previous section. The LLRF system
provides a tool to measure the microphonics in the system
as shown in Fig. 6. The LLRF measures the peak forward
power and detuning with a time resolution of 10 $\mu$sec
and 100 $\mu$sec respectively. We ensure that the peak microphonics
detuning is $\leq 50$Hz for stable operations while the peak
power should be less than the maximum output of the SSA
connected to the cavities, 5 kW for stiffened and 10 kW for
un-stiffened. If deemed necessary, we can use the spectrum
measurement to determine the frequencies of strong vibra-
tions in the cryomodule and then activate the ANC algorithm
on these sources.

**Step 6:** Stability of electric field in the RF cavity depends
on the proportional and integral gains of the field control loop
(cavity Loop). We complete steps 4 and 5 with some default
parameters for the control loop, namely with a normalized
proportional gain of about 100 and a zero integral gain. Then
we measure the standard deviation of the field amplitude and
phase as a function of the feedback gains in order to optimize
the performance of feedback control.

**CONCLUSION**

The MLC housing six 7-cell cavities will be used for
energy recovery in CBETA with a nominal accelerating voltage
of 6 MV on each cavity. Three of these cavities are
fitted with stiffening rings in order to reduce their sensitiv-
ity to external vibrations. The vibrations in this TESLA
style cryomodule drive large microphonics detuning of the
SRF cavities comparable to their bandwidth thus limiting
the field stability in the presence of available maximum RF
power. Keeping this in mind, the un-stiffened cavities are
powered by SSAs capable of generating 10 kW while the
others can generate 5 kW. Initial testing of the high power
RF components led to failure of the circulators, eventually traced to a manufacturing defect originating from a material with a high loss tangent. One of the RF amplifier slices also failed during initial testing due to large reflected power from a faulty connector damaging the sensitive transistors. After repair all RF components are operating normally and we have tested everything to full power. We also carefully optimized various cryogenic system control loops which regulate Helium level and pressure inside the cryomodule in response to varying levels of thermal load during RF operations. The performance of the room temperature Helium blowers which maintain 2 K vapour pressure inside the cryomodule strongly suggests that the thermal dissipation of the cavities is within the expected range.

The RF system commissioning involves tuning all cavities to resonance and setting various LLRF control parameters to ensure stable operations. Once the system was sufficiently optimized in the initial days of operations, we have automated many of these steps which are run by a sequencer everyday before starting beam operations. We start by tuning the cavities to resonance using the slow tuner system, followed by reducing the leakage of forward power into the cavities by optimizing the offsets of the LLRF DACs. Then we set the parameters which allow the LLRF to safely trip off, protecting the system from permanent damage. After this, we close the feedback loop to maintain a stable field of 1 MV inside the cavity, and measure the phase offset of the field probe signal. Finally we measure microphonics and field stability and optimize the field and resonance control loops for stable operations. Future work will involve automating steps 5 and 6 of the startup procedure with special emphasis on establishing stable high-current energy recovery operations with no spontaneous trips.

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REFERENCES


