

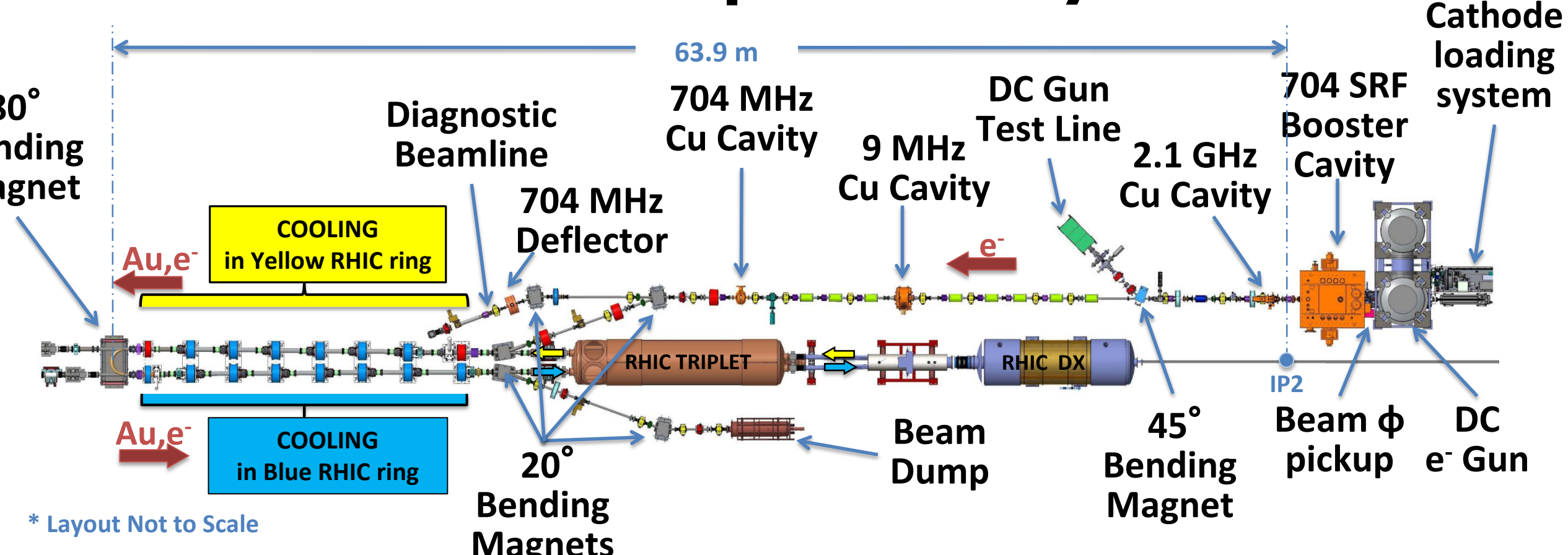
# Energy Measurement and Stabilization for LEReC

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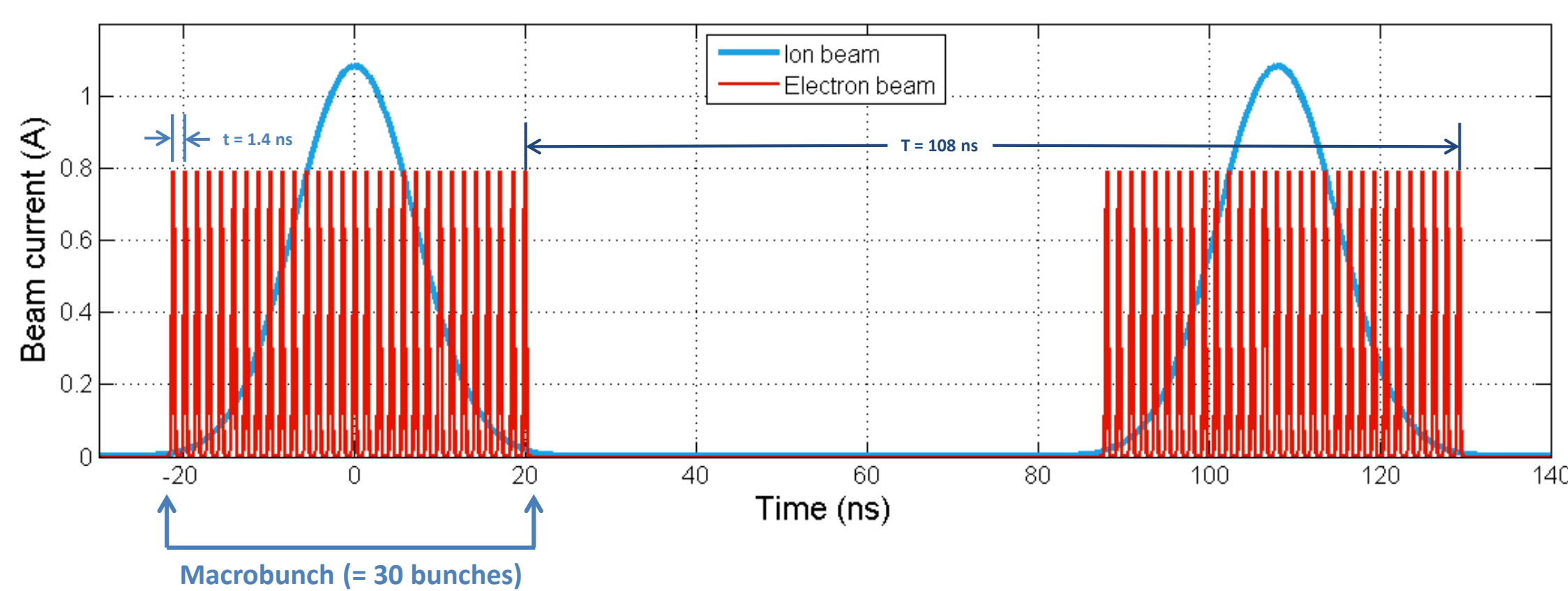
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The Low Energy RHIC electron Cooler (LEReC) is presently being commissioned at BNL to improve the luminosity of the Relativistic Heavy Ion Collider (RHIC) at low energies. LEReC is the first RF linac-based electron cooler with bunched beam cooling. A critical beam parameter for electron cooling is the velocity difference between the electrons and ions. This results in tight tolerances on the electron beam energy spread (5e-4 rms) and long-term energy stability. Two main beam-based diagnostics are used to measure the average energy and energy spread of the beam. Several passive and active measures are used to stabilize and correct the amplitudes and phases of the various RF cavities to meet the specification.

## LEReC Component Layout



## Time Structure of Electron Beam



## LEReC RF Cavities and Energy Spread Reduction

The four RF cavities in the injector and transport sections must accelerate the beam to the desired energy and also perform an RF gymnastic to reduce the energy spread.

### 704 MHz SRF Booster Cavity

- Provides acceleration to the desired beam energy and produces an energy chirp to stretch the electron bunches

### 2.1 GHz Warm Cavity (3rd Harmonic)

- Provides RF curvature correction to compensate 704 MHz curvature

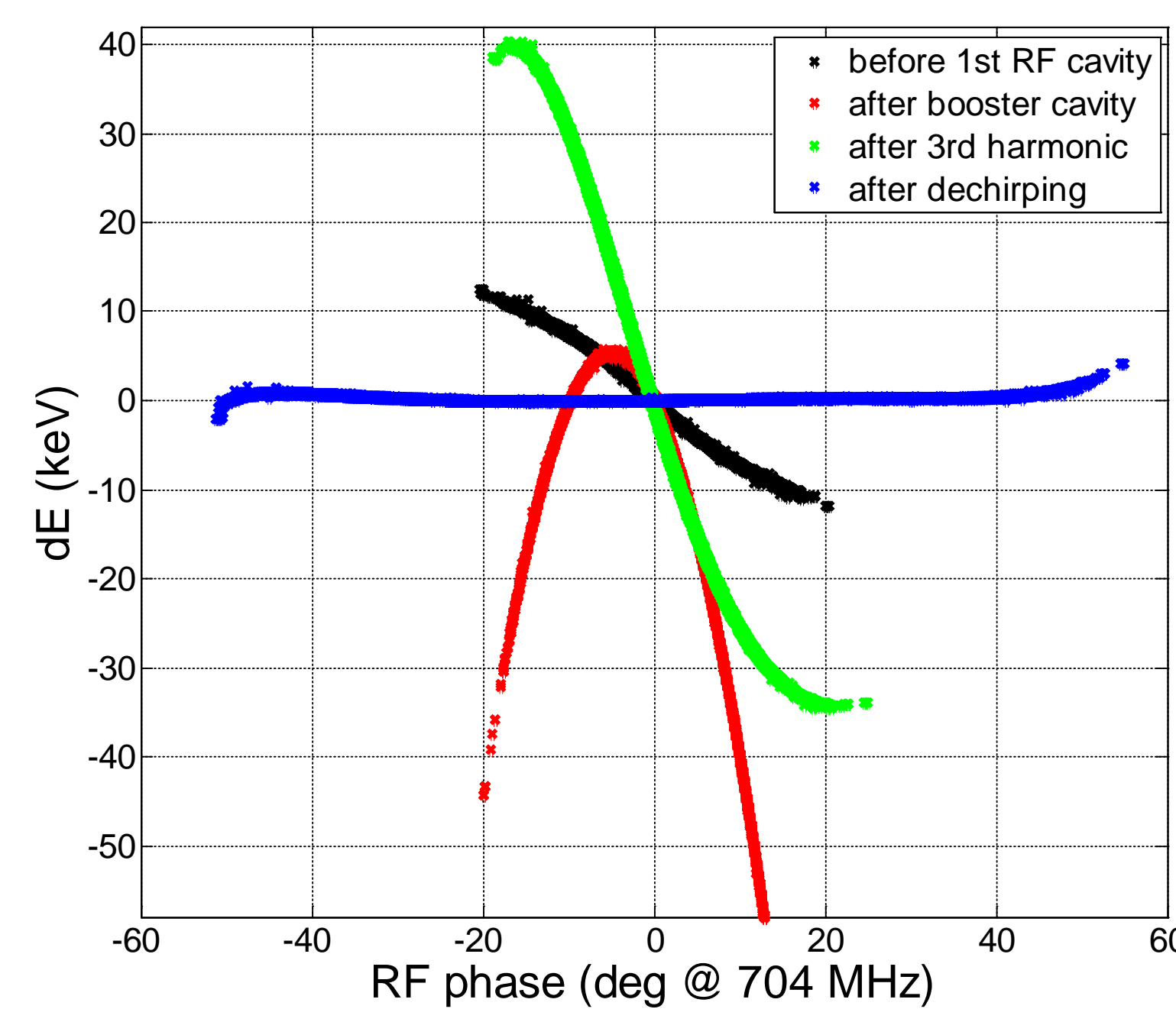
### 9 MHz Warm Cavity

- Provides an energy kick which varies along the macrobunch to compensate linear periodic transient beam loading, i.e. the average energy loss from the first to the last bunch of a macrobunch

### 704 MHz Warm Cavity

- Removes energy chirp from the stretched bunches to minimize the energy spread

The chirp/dechirp also reduces the effect of errors in the cavity voltage on the average energy of the final beam. For example, an amplitude error at the booster cavity results in a final energy error about 40% as large.

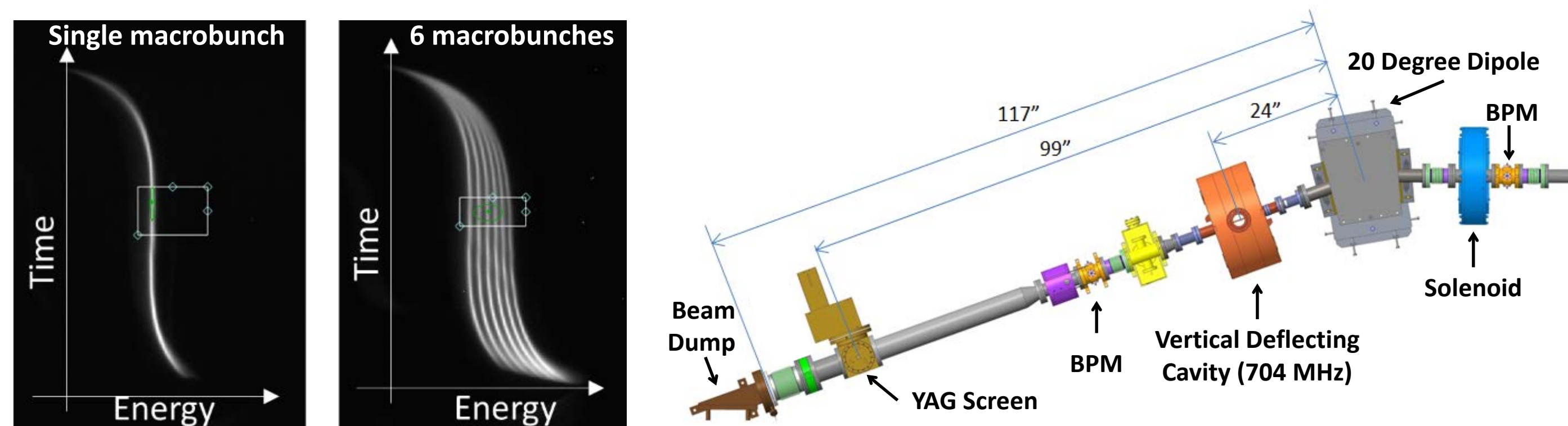


These distributions are from a simple model that excludes space charge after the booster cavity. They are not fully accurate, but illustrate the ballistic stretching of the bunches. Energy error is shown relative to the synchronous particle at each location.

## Diagnostic Beamline and Deflecting Cavity

A 704 MHz Vertical Deflecting Cavity is used in the diagnostic beamline for measuring longitudinal phase space. It produces an RF phase dependent vertical kick to streak the beam on a YAG screen. Dispersion from a dipole provides (relative) energy measurement. Analysis code "slices" the image to determine energy spread as a function of RF phase.

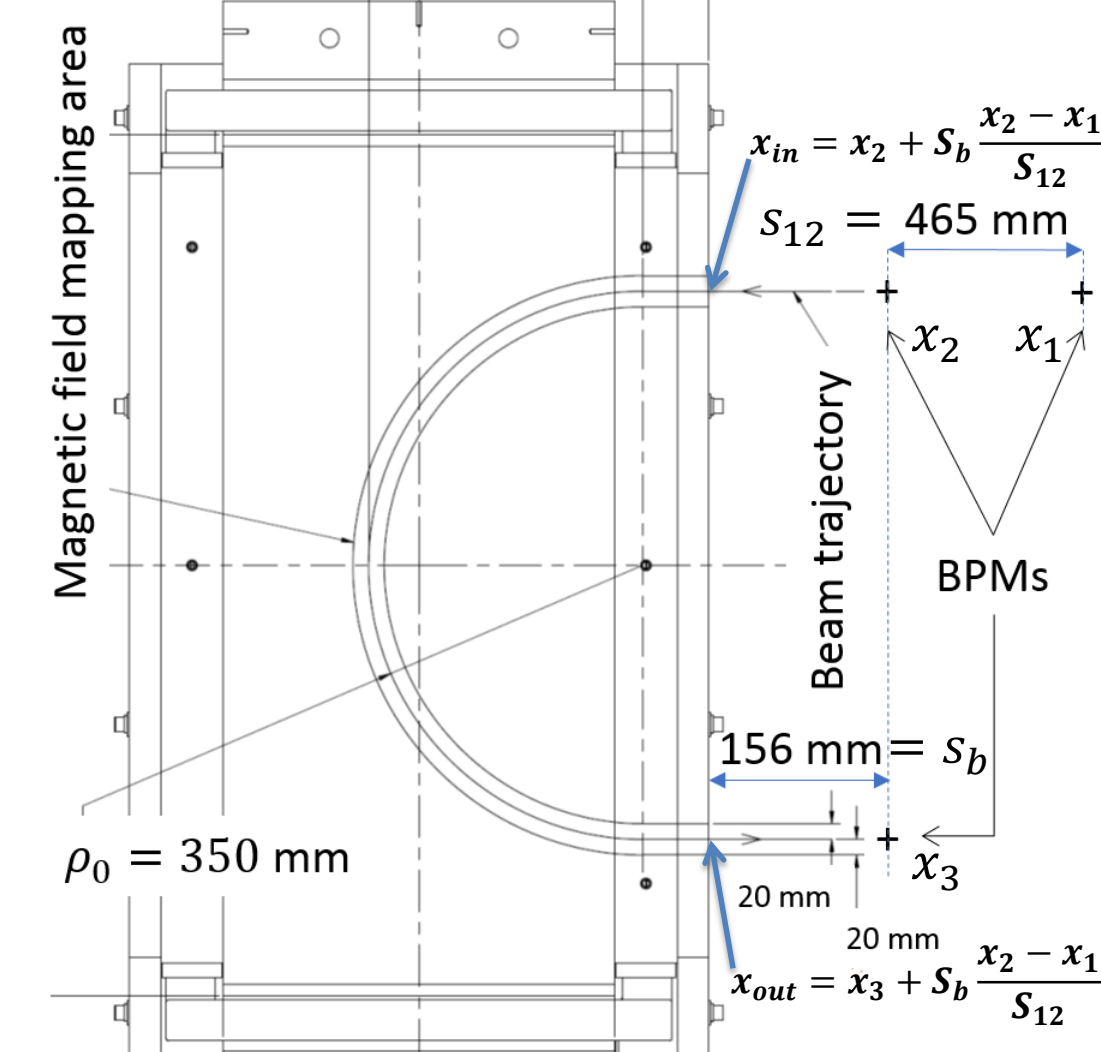
This is the primary diagnostic for measuring energy spread and setting the relative phases and amplitudes of the RF cavities to minimize dE. When the 9 MHz cavity is properly set to minimize the beam loading from the first to last bunch of a macrobunch, the width of the individual macrobunches is minimized. The diagnostic line can only measure very low duty cycle pulsed beam, which is affected by transient beam loading of the DC gun and RF cavities. A feedforward correction for the RF cavities was implemented, but without correction on the DC gun, it was ineffective. A correction algorithm using measured responses to changes in RF cavity amplitude and phase to correct the energy spread has been developed.



## Acknowledgements

We would like to acknowledge the many valuable contributions of our colleagues in the Accelerator Physics, Instrumentation, Controls, Operations and RF Groups in the Collider-Accelerator Department. In particular, V. Schoefer and S. Seletskiy led much of the work related to the diagnostic beamline and the 180° magnet spectrometer.

## 180° Bending Magnet Spectrometer

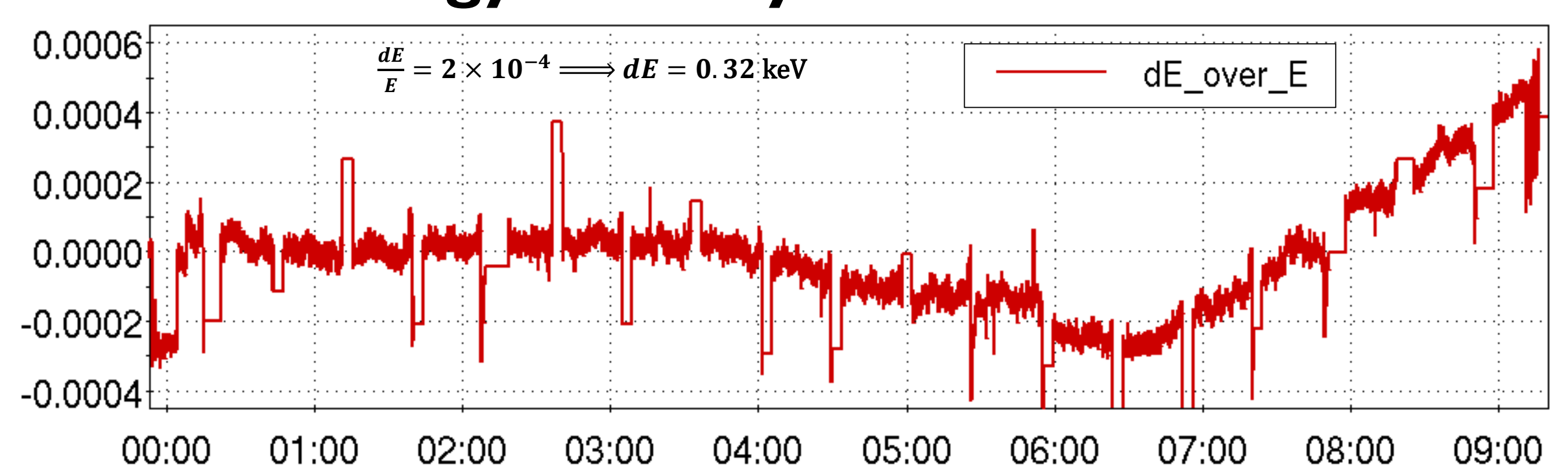


The 180° bending magnet is used as a spectrometer to measure the average beam energy. Two BPMs upstream of the bending magnet and one BPM downstream are used to determine the position and angle at the magnet entrance and position at the magnet exit. The field of the magnet was mapped and is monitored in real-time with a custom NMR probe optimized for the low field of the bending magnet (20 – 30 mT).

The field probe readings during operation are used to scale the field map. A hard-edge approximation of the magnet was shown to be sufficiently accurate when benchmarked against tracking particles through the field map. This hard-edge approximation is used to calculate the energy from the BPM readings. This measurement is available whenever there is electron beam in the cooling section, so it can be monitored continuously or used as input to a beam-based energy feedback.

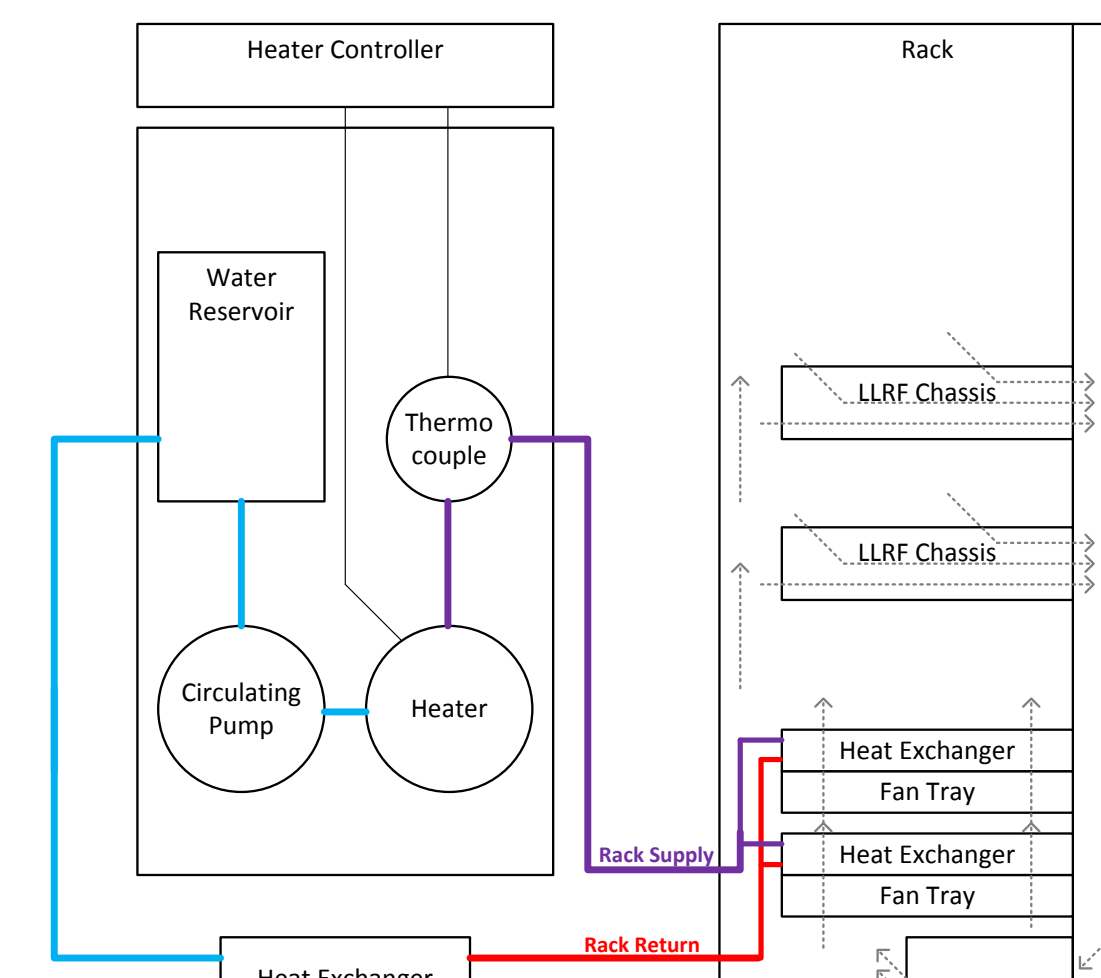
Data is sent from the BPM electronics to one of the LLRF controllers over three dedicated unidirectional serial links. These links use 10 Mbps biphasic encoding similar to the RHIC Event and Real-Time Data Links. The controller that receives the BPM data calculates the energy and broadcasts it on the Update Link to other LLRF systems.

## Energy Stability Measurements



Due to the busy LEReC commissioning schedule, it was difficult to find times when the electron beam ran without many configuration changes. There were a few overnight shifts where the beam was left running in 76 kHz mode (i.e. one electron macrobunch per RHIC revolution period). The energy measurement over about 9 hours from one of these shifts is shown here. The flat spots in the data (and spikes just before or after) are from periods of time when the electron beam was off. The energy drift is well correlated with the outside temperature, which increased 10° F over 3 hours starting at sunrise. Over a longer time period, or a day with larger temperature variations, the energy drift would be worse.

## Passive Stabilization



Passive stabilization measures have been taken to reduce the effects of thermal drift on electronics in the LEReC LLRF racks.

- The LLRF racks are temperature regulated with water cooled heat exchangers. The water supply for these comes from a closed loop system that rejects heat through another heat exchanger to a chilled water system. The stability of the chilled water is only about  $\pm 2^\circ \text{C}$ , so a 1.5 kW heater is used to regulate the closed system to about  $\pm 0.2^\circ \text{C}$ .

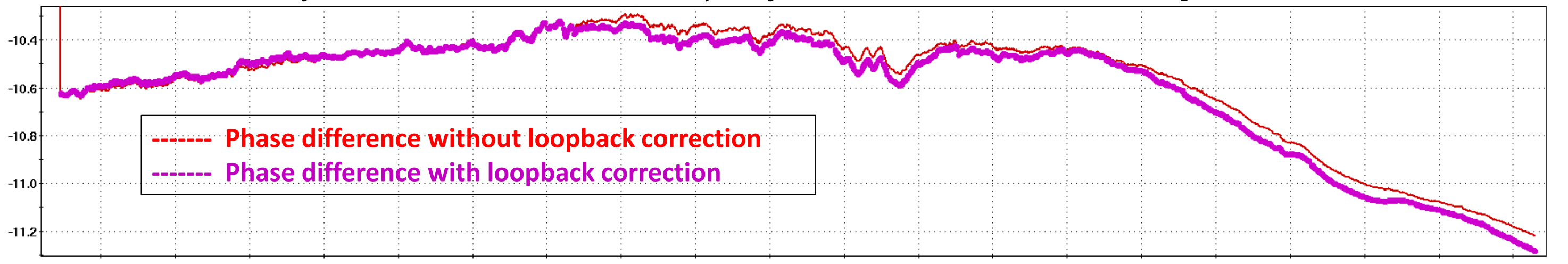
- All RF components for the downconverters, upconverters, and LO generation are thermally tied to large  $\frac{1}{4}$ " aluminum plates to stabilize their temperatures.

Channel-to-channel drift between ADCs is on the order of a few  $10^{-4}$  in relative amplitude and a few  $0.01^\circ$  in phase over 24 hours. This drift is similar whether the ADCs are on the same or different boards and whether the downconverters are in the same or different chassis. At this point, we have not determined what amount of this drift is caused by the splitters and cables used for testing and what amount is from the LLRF electronics.

## Cable Drift

The cable route from the LEReC LLRF racks to the cavities in the RHIC tunnel runs outside for approximately 50 feet. An additional cable route, where the outdoor run is shorter and travels through an insulated and temperature controlled conduit was added. Bundles of 3 cables were run through the conduit to allow using two cables as a loopback connection to monitor drift. The temperature controlled cable path is significantly longer than the original cables, so we run the LLRF feedback using the original cables. A correction factor will be applied in the LLRF feedback based on the cavity pickup measurement using the temperature controlled cables compensated for the measured drift of the loopback signals.

The phase difference between the outdoor pickup cable and temperature controlled pickup cable for the 704 MHz warm cavity is shown. The cavity amplitude and phase drift is an order of magnitude larger than drift measured for the LLRF electronics. The loopback compensation applied is much smaller than the measured cavity drift, so we believe the majority of this drift is due to the exposed outdoor cable.



## Energy Feedback / Active Stabilization

During the 2019 LEReC commissioning run, the average energy was corrected manually by the physics shift leader. The beam arrives near the zero crossing of the 704 MHz warm cavity, so small energy adjustments can be made with the phase of this cavity, without much impact on the energy spread.

Our plan for the 2020 LEReC run is to have the corrections for the cable drift operational, which is expected to reduce, but not eliminate, the energy drift. In addition, a feedback system will modulate the phase of the 704 MHz warm cavity to hold the measured average energy at the desired value. Since this energy feedback will compensate any source of error with a single correction, it is possible that the energy spread will degrade while the average energy is held constant.

To mitigate against this possibility, we will have to periodically measure the beam's longitudinal distribution in the diagnostic beamline. If necessary, during the measurements, the energy spread could be corrected and the cable drift and average energy corrections reset. This procedure could be automated and executed in between RHIC physics stores.