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***Differential Current Measurement in the BNL
Energy Recovery Linac Test Facility***

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DIFFERENTIAL CURRENT MEASUREMENT IN THE BNL ENERGY RECOVERY LINAC TEST FACILITY

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ABSTRACT

An Energy Recovery Linac (ERL) test facility is presently under construction at BNL [1,2]. The goal of this test facility is to demonstrate CW operation with an average beam current greater than 100mA, and with greater than 99.95% efficiency of current recovery. This facility will serve as a test bed for the novel high current CW photo-cathode [3,4], the superconducting RF cavity with HOM dampers [5,6], and the lattice [7,8] and feedback systems needed to insure the specified beam parameters. It is an important stepping stone for electron cooling in RHIC [9], and essential to meet the luminosity specifications of RHICII [10]. The expertise and experience gained in this effort might also extend forward into a 10-20GeV ERL for the electron-ion collider eRHIC [11]. We report here on the use of a technique of differential current measurement to monitor the efficiency of current recovery in the test facility, and investigate the possibility of using such a monitor in the machine protection system.

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Keywords: Energy Recovery, Recirculating Linacs, Diagnostics, Machine Protection, Current Measurement

1. INTRODUCTION

The overall layout of the test facility is shown in Figure 1. Visible are the control room, two service rooms, and the shielded ERL cave. Injection energy will be 2.5MeV, and maximum beam energy will be 20MeV. The lattice has been designed to permit the possibility of a second acceleration pass, resulting in a high current 40MeV beam perfectly suited for a far-IR FEL. Two operating modes are anticipated for the test facility, one maximizing the bunch charge and the other the average beam current. Additional beam parameters for the high charge/current modes include: average beam current 0.2A/0.5A, bunch repetition rate 9.4MHz/703.75MHz, charge per bunch 20nC/1.3nC, and normalized emittance 30mm-mrad/2mm-mrad. The desired efficiency of current recovery is greater than 99.95% in both operating modes. A more detailed layout of the Ring and the associated diagnostics is shown in Figure 2. Details of the injection line and its diagnostics are not shown in this figure.

The figure shows the locations of the two DC Current Transformers [12,13] proposed for the differential current measurement, one each in the injection and dump lines. The principle of the measurement is to connect the two toroids with a figure-8 winding, and then use the output from the second toroid as input to a feedback loop that injects current into the figure-8 winding to drive that output to zero. The output of the first toroid is then the differential current measurement. This approach eliminates the dynamic range problem of accurately measuring a small difference between two large signals, and permits some compensation of variations resulting from pickup sensitivity to temperature and magnetic field fluctuations.

2. MEASUREMENT RESOLUTION

A differential current measurement accurate to 1 part in 10^{-4} will give 20% resolution on the desired 99.95% efficiency of current recovery. Listed below are the various factors which must be considered in attempting to estimate the possible measurement resolution, as well as how these factors are mitigated by the nulling technique. Numerical values are taken from the Bergoz specification [12,13]. With the exception of gain linearity, they are independent of beam current. These factors are listed in what we presently consider to be the order of increasing importance.

- Gain Linearity - The specification for gain linearity is 1 part in 10^{-6} per mA of beam current. With a beam current of 100mA, this becomes 1 part in 10^{-4} . If nulling is effective to the desired measurement accuracy of 1 part in 10^{-4} , the effect of gain linearity would then be ~ 1 part in 10^{-8} , and would be of no consequence in the accuracy of the differential current measurement.
- Magnetic Core Noise - More commonly called 'Barkhausen noise' or 'flux noise', this noise results from the magnetic domain boundaries, and is typically several tens of dB above thermal. The measured value [13] in the NPCT is $\sim 0.3\mu\text{A}/\text{rootHz}$. With a 10Hz measurement bandwidth and 100mA of beam current, the resulting 1 μA of flux noise would contribute noise at the level of ~ 1 part in 10^{-5} . This noise is stochastic, contributions between the two transformers will be uncorrelated, and no benefit will be derived from the nulling technique for this source.
- Field Sensitivity - The sensitivity to spurious fields is $\sim 100\mu\text{A}/\text{Gauss}$. The NPCT as delivered incorporates reasonably sophisticated magnetic shielding to achieve this specification. Additional magnetic shielding can be added, at the expense of precious longitudinal space in the injection line. The effect of

the nulling technique will be to eliminate global field sensitivity, such as that due to the Earth's magnetic field. The unknown is the extent to which local field variations can be eliminated. If these variations are stable in time, they can be calibrated out when beam is not present. For 100mA of beam current, reduction of spurious field differences between the two toroids to the level of 10^{-2} Gauss would result in spurious field noise of 10^{-5} .

- Temperature Sensitivity - The sensitivity to temperature is predominately in the sensor, at the level $\sim 5\mu\text{A/K}$. Sensitivity of the electronics is less than $0.1\mu\text{A/K}$. The effect of the nulling technique will be to eliminate global temperature sensitivity, such as slow changes in ambient temperature. Attention should be given to the placement of heating and cooling ducts, to insure that the local environment is as similar as possible at the locations of the two toroids. In addition, temperature regulation can be employed. If we assume that temperature regulation can limit the temperature difference between the two toroids to 0.2K, this would contribute 10^{-5} to the measurement uncertainty. As in the case of local field variations, local temperature variations can be calibrated out when beam is not present. However, the time scale of local temperature variations can be anticipated to be shorter than that of local field variations, so if this form of calibration is required care must be taken to insure that it does not become disruptive to machine operations.

Summarizing the above considerations, it appears that for a 100mA beam the measurement accuracy and resolution needed for a differential current monitor that permits verification of 99.95% current recovery is possible without undue effort. The primary concerns are temperature and magnetic field fluctuations.

3. MACHINE PROTECTION

The obvious place to look for guidance in considering the use of differential current measurement is in the experience at operating facilities. We assume that the threshold for damage is approximately independent of beam energy. The damage threshold is certain to be something less than an integrated loss of $10\mu\text{A}\cdot\text{sec}$ [14]. In the present discussion we assume a threshold of $1\mu\text{A}\cdot\text{sec}$. The operational criterion used at Jefferson Lab is $0.025\mu\text{A}\cdot\text{sec}$ [15]. This sits on top of a known loss of $\sim 1\mu\text{A}$. This measurement is accomplished with resonant cavity pickups, and the attained resolution is remarkably good. The discussion of the previous section suggests that the limit of the proposed NPCT approach to differential current measurement will be somewhere in the vicinity of $\sim 1\mu\text{A}$. Whether this will prove useful for machine protection at the BNL ERL test facility, or whether the measurement can be refined to improve the resolution, are subjects that require further consideration.

4. CONCLUSION

We have presented a discussion of some of the factors which must be considered in evaluating the use of DCCTs in a difference mode for the purpose of monitoring the efficiency of current recovery in the BNL ERL test facility. Our preliminary conclusion is that such an approach has a good potential to be successful. The possible use of such a monitor for machine protection requires further study. If such a monitor is to be implemented, it is essential to get the DCCTs in-house as soon as possible, to permit detailed investigation of the performance limitations. And finally, a caution should be introduced here. It is essential to avoid adding additional noise with the hardware utilized for nulling. Given that the Barkhausen noise is well above the thermal noise floor, proper attention to detail should permit this.

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FIGURE CAPTIONS

Figure 1. Overall layout of the BNL ERL test facility.

Figure 2. Layout of the ERL Ring, showing locations of proposed diagnostics.

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Bergoz uses the terms 'Parametric Current Transformer' to describe their DCCT, in reference to the non-linear process that permits measurement of the DC current. A new PCT has become available, the 'NPCT'. Documentation on the NPCT was not available on the Bergoz web site at the time of this writing.

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Figure 1

Figure 2