DESIGN AND PERFORMANCE OF THE BIASED DRIFT TUBE SYSTEM IN THE BNL ELECTRON LENS *

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Abstract

The Electron Lenses [1] in RHIC are designed with a series of biased drift tubes through which the electron beam propagates in the opposite direction of the RHIC ion beams. An electric field gradient created by selectively biased drift tubes sweeps out ions generated through residual gas ionization and trapped in the central longitudinal magnetic field where the electron beam interacts with the RHIC beam. The image currents induced on the drift tubes by the RHIC beam develop high voltages at RF frequencies that are detrimental to the electron and ion beams. This paper presents the design of the biased drift tube system along with the commissioning results of the DC bias and instrumentation features.

INTRODUCTION

In an effort to refocus the RHIC beam and compensate for defocusing as a result of beam-beam interactions, two Electron Lenses (e-Lenses) have been installed in the RHIC tunnel, one for Blue and one for Yellow beams (the two counter rotating particle beams in the collider). The electron beam of the e-Lens device has adjustable energy of 0 – 10 keV, pulse width of 300 ns – DC or frequency up to 80 kHz, and current from 0 – 1 A. As the electron beam propagates, at these relatively low energies, through the region of interaction with the RHIC beam and towards the beam dump, its size is constrained by a continuous magnetic field set up by multiple solenoid magnets (see Fig. 2) with a super conducting solenoid covering the interaction region. As the magnetic field varies along the trajectory, with the highest field (6T) in the central interaction region, a magnetic potential well is formed where positively charged ions generated from residual gas can be trapped. Ions trapped in the interaction region would neutralize the electron lens field. To avoid this situation, a series of selectively biased drift tubes surrounds the electron beam trajectory to set up a gradient electric field to pull the ions out of the interaction region towards the negatively biased reflector [2] in the collector, or beam dump. Fig. 1 shows a simulation, of the distribution of drift tube "DT" potentials (U_el) and the magnetic field strength along the beam axis. This is updated from a previously published version [2] accounting for drift tube layout modifications. The voltage gradient extends into the magnetic well to extract the ions.

The concern with biased drift tubes is the high impedance they present to the image currents of the RHIC beams. This results in high voltages at RF beam frequencies being induced on the drift tubes. This condition would perturb the low energy electron beam as well as introduce a high impedance to the RHIC beam. Thus a path must be provided for these currents while allowing a DC bias voltage to be applied to the drift tubes.

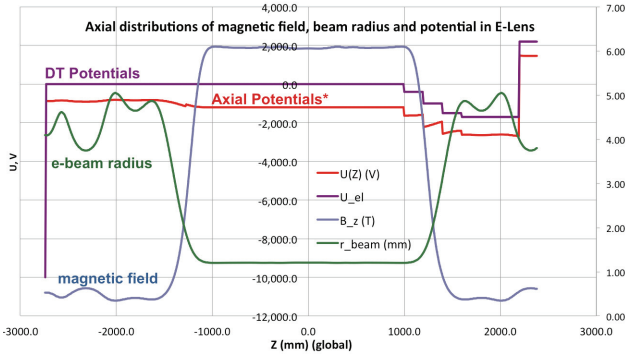

Figure 1: Voltage gradients & magnetic well.

The above requirements call for an RF bias tee to apply a DC bias voltage from a power supply while allowing RF power to pass through to a dissipating load; thereby isolating the DC supply from the RF power. As shown in Fig. 2, there are 9 drift tubes (DT00 is not installed and DT04-2 & -3 are connected together.) 7 of which require bias tees. A signal path is provided by custom vacuum feedthroughs rated for 10 kV DC with low RF insertion loss.

RF SPECTRUM & POWER

The induced signal spectrum was simulated using Particle Studio for a RHIC beam of 10^{11} protons with 20 cm RMS bunch length. Thus the required frequency range of the bias tee and feedthroughs is 50 – 500 MHz, as shown in the spectrum in Fig. 3. In order to roughly match the impedance of the drift tube structure to the 50 Ω cables, each drift tube requires two connection points and thus two bias tees. The power generated at each drift tube was simulated. The results predicted values reaching as high as 150 W per connection. Although this level is reasonable for the feedthrough, it complicates the design of the bias tee. Locating the bias tees a long distance away from the E-Lens takes advantage of the attenuation in the RG213 cable at the frequencies of interest; thereby reducing the power requirements of the bias tee. Recalculating the power requirements for each drift tube, accounting for the attenuation in the cable, the maximum

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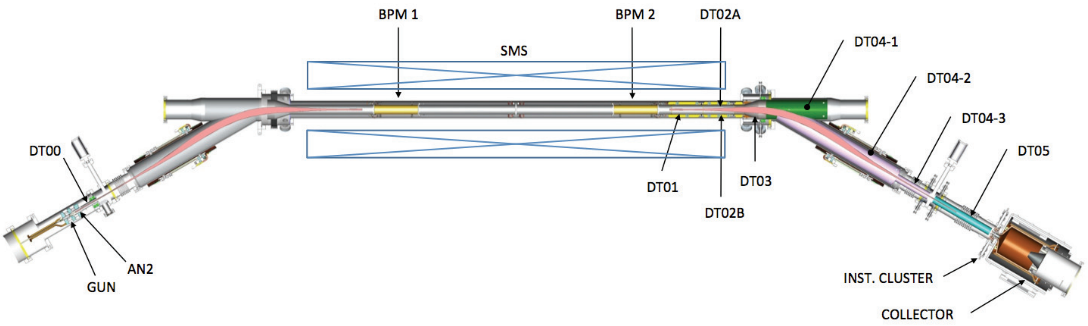

Figure 2: E-Lens vacuum system (green) with magnets and drift tubes enumerated.

power dissipation was reduced to 20 W per connection; where the dissipation in the cable is ~ 0.5 W/ft.

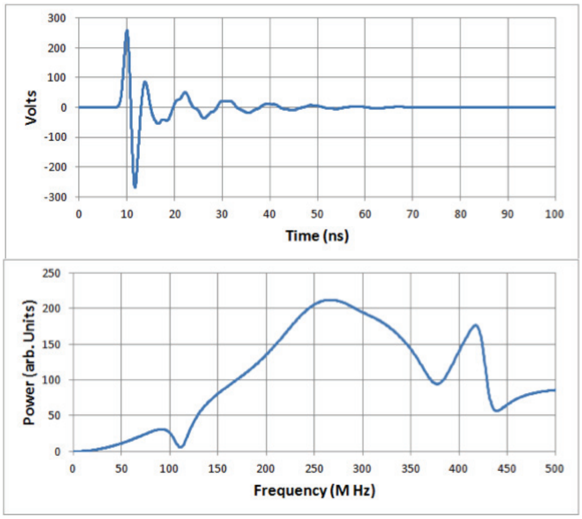

Figure 3: RHIC beam bunch Simulated signal on a drift tube with resulting frequency spectrum.

FEEDTHROUGH DESIGN

In order to keep a 50 Ω coaxial transmission line through the vacuum wall, a feedthrough with both air-side and vacuum-side coaxial connectors is required. Stringent vacuum requirements mandated the use of bakeable materials and thus prompted the custom design of a double-sided HN connector with a quartz insulator. The choice of quartz was made as it had the closest dielectric constant to the PEEK insulation in the standard single ended design. The HN connector was chosen for its HV rating and good RF response. The feedthrough was designed by SST [3] and bears part number FA25906 and comes welded in a 2.75 in. conflate flange. Tests of the final product revealed a maximum insertion loss of -16 dB at up to 1 GHz. Due to the varied geometry of the vacuum system, only some of the drift tubes require in-vacuum coaxial cables. At the other locations, single ended feedthroughs were used and positioned directly over the drift tube with a spring-loaded pin making contact. Airside connections were made using the Amp model 82-804 HN connector for RG8/RG218, as this series is rated at 7 kV as opposed to other manufacturers with rating only up to 4 kV.

BIAS TEE DESIGN

While bias tees rated for 100 V are common in the communications industry; high voltage bias tees rated up to 10kV are not available. In this application, a bias tee is required to handle up to 10 kV of DC bias while simultaneously passing up to 20 W of RF power in the frequency range of 50 – 500 MHz. A prototype bias tee was built around a high voltage ceramic chip capacitor which was installed between two 50 Ω microstrip transmission lines. The high frequency RF power sourced by each drift tube was isolated from the DC supply input using a series of RF choke inductors. The simplified circuit is shown in Fig. 4 where the drift tube connects to J4, the HV power supply connects to J7, and the RF load connects to J6.

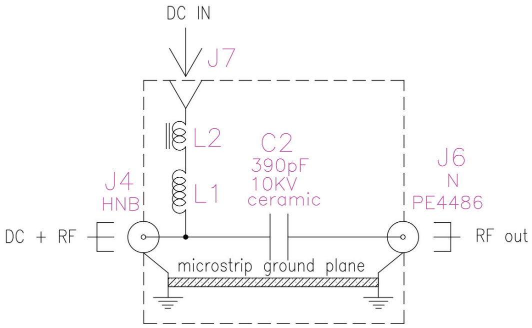

Figure 4: Bias Tee schematic.

The prototype was fine-tuned until a return loss of less than -14 dB (< 4 % reflected power) through a 50 – 1000 MHz band was obtained. It was then sent to Jon Barth at Barth Electronics [4] where the design was further optimized to fit inside of an aluminum enclosure. A HV connector was also added to accept the bias voltage input. The finished product was given model # 45350 and measures 2 x 3 x 4 in.

Production Design

To produce a final design to pass greater than 90% of RF energy from 50 to 1000 MHz through a Bias T required a special inductor and capacitor design. Moreover, each of the elements in the Bias T had to withstand 10KV bias voltage. The connectors, capacitor, and bias inductor used cured pieces of Sylgard (potting material) laid on top while fine tuning the layout to achieve minimal TDR reflections when fully potted. The final design, like the prototype, is comprised of the HV capacitor between two striplines each terminated by a 50 Ω connector, and a series of inductors on the HV input, as shown in Fig. 6.

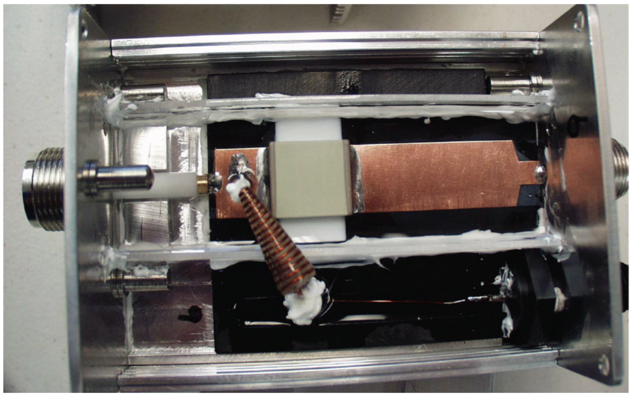

Figure 6: Bias Tee before potting. Components left to right: HNB connector, tapered inductor, HV capacitor between striplines, and N connector.

A number of HV capacitor concepts were attempted while trying to achieve a low S11 response up to 1 GHz but with little success. One special capacitor design was found, model C185 made by Dearborne / Eurofarad [5,6], that provided the full voltage isolation of 10 kV in a single surface mount package. The multilayer chip capacitor is made of titanium oxide (plus various other oxides) and measures a mere 16.6 x 15.2 x 6 mm. This capacitor provided the necessary low resonance effects up to 1 GHz. The largest capacitor value available at 10 kV was 390 pF. Such a small value of capacitance was made possible to have low in-band insertion loss by making use of its series resonance at 300 MHz that happens to fall in the middle of our frequency band.

An inductor to pass DC bias without troublesome shunt resonances over the required bandpass was needed. Although DC current requirements for a bias T are usually limited to a few mA, this design required higher pulse current capability to deal with the eventual impact of the electron beam on the drift tubes. It was designed to withstand a pulse of 1A for 100 µs. A small toroid in series with a tapered helical inductor was used to improve the flat frequency response of the bias tee. The tapered inductor was wound with number 22 copper wire; which was used in a previous design that had an inherently extremely wide bandwidth, avoiding resonances inherent in helical inductors.

The "HNB" Connector

Experience at Barth Electronics has found that Teflon, with compensated coaxial cable transition, will withstand half microsecond pulses at 12kV. While the HN connector will withstand 15kV DC, the Teflon connector interface will break down from multiple partial discharges in the small air gap interface. This limits long term pulse amplitudes to 12 kV.

High voltage high-speed requirements of the HN connector over the years lead Barth Electronics to develop their special HNB connector, with modifications to the HN design and tighter tolerances. The HN connector in the prototype was changed to the HNB type; although its interface to the stripline required a special design to achieve uniform impedances at the different metal and dielectric transitions throughout the connector.

RF Response Testing

The final RF design was tested primarily in the time domain by minimizing the reflection coefficient at 100 to 300 ps rise time. This allowed adjusting for minimum reflections at each element in the time domain and provided an overall minimum SWR beyond 1 GHz. The total HV assembly held close tolerances. The HNB connector at the input to the stripline and the N connector at the other end kept the S11 return loss very low to allow for some higher reflections from the HV capacitor transition and tapered inductor. Final frequency domain measurements showed a good S11 response of < -20 dB over 25 – 1250 MHz, as shown in Fig. 7.

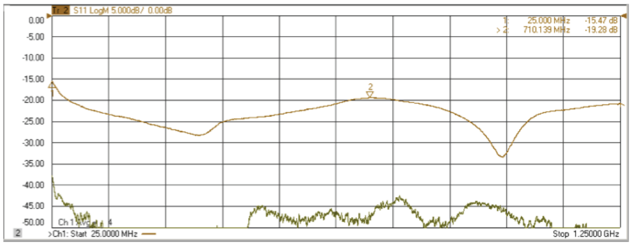

Figure 7: Return Loss Response (S11) < -20 dB 25 – 1250 MHz.

BEAM LOSS TO DRIFT TUBE

In the event that there is a strike of the electron beam to the drift tube, the drift tube voltage would quickly charge to the beam voltage and create a virtual cathode. To avoid this, a capacitor was added to the high voltage bias circuit to absorb the beam current and stabilize the drift tube voltage over 100 µs – long enough for the machine protection system (MPS) to detect a beam loss. To limit the voltage change on the drift tube to 1 kV with a 1 A (maximum) beam current in 100 µS, a 100 nF capacitor is required. An aluminum polyester wound film capacitor was chosen, model CH84 from Capacitor Industries [7], with high withstand voltage, stable capacitance, and good high frequency characteristics. Moreover, in order to protect the bias power supply from reverse overcharging during a beam strike, a 30 kΩ resistor was added in series with the connection to the bias supply, as shown in Fig. 8.

Bias Tee Chassis

The high voltage resistors and capacitors are visible in the simplified diagram of Fig. 8, depicting a drift tube in the beam path with its dual connections to bias tees installed in a chassis. As each drift tube requires two bias

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tees, one chassis containing both bias tees and high voltage resistor and capacitor serve each drift tube via two lengths of RG213 cable complete with HN connectors. Fig. 2 shows that there are 7 drift tubes requiring bias tees and thus there are 7 dual bias tee chassis for each E-Lens machine. A total of 36 custom bias tees were produced by Barth Electronics for this project, including spares.

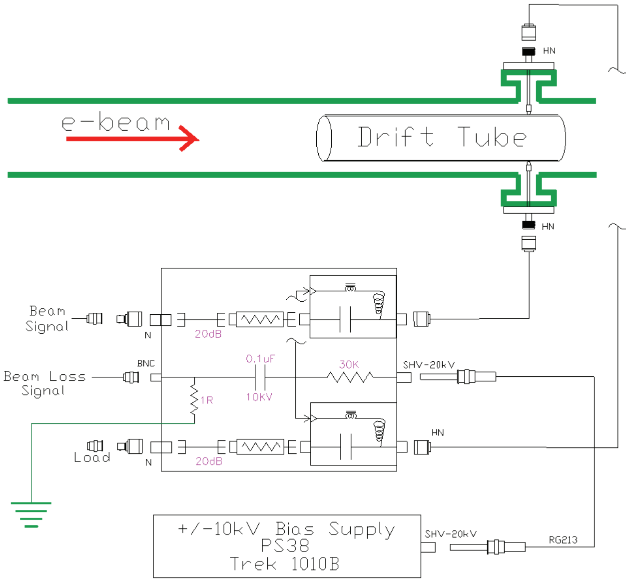

Figure 8: Bias Tee chassis with drift tube.

Drift Tube Instrumentation Signals

The RF power induced on the drift tubes is dissipated in the ~250 ft of RG213 cable and in the attenuator connected to the bias tee in the chassis, as shown in Fig. 8. The other side of the attenuator is either terminated or used for measuring the beam-induced signal. A beam loss signal is generated by the voltage across a 1 kΩ resistor in the ground path of the 0.1 μF capacitor used to absorb the current during a beam strike. Fig. 9 shows an example of these signals recorded during machine commissioning. The top trace is the beam loss signal from a 36 μs pulse @ 130 mA directed into the drift tube. The bottom trace is the signal from the RHIC beam as it passes through the drift tube.

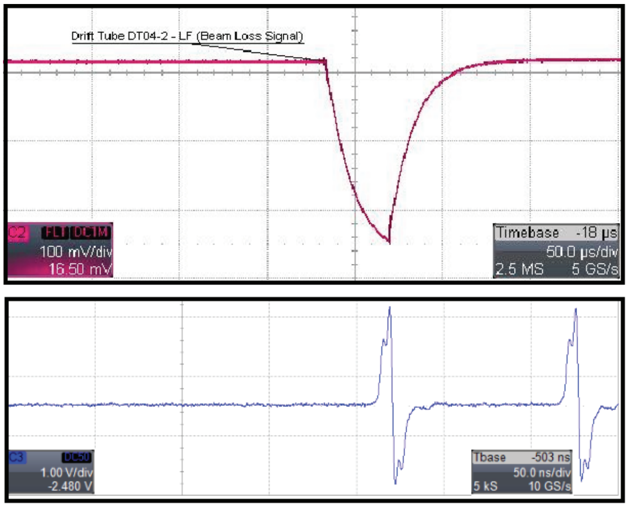

Figure 9: Bias Tee signals: (top) 130mA 36μs beam loss to drift tube, (bottom) RHIC beam signature.

While the signals will be available to monitor with an oscilloscope, the low frequency beam loss signals, one per drift tube, are connected to integrating electronics that are gated & held at 1 Hz. The analog voltage output for each signal is logged at a 1 Hz rate in the archives for troubleshooting after a beam loss event.

FUTURE PLANS

Status and Schedule

Having finished the commissioning of the electron beam transport and instrumentation in the Blue E-Lens this past July, work is underway to complete the installation of the Yellow E-Lens along with some modifications to the Blue E-Lens. Work continues during the current RHIC shutdown and complete testing of the two E-Lens devices is planned to begin parasitically to RHIC operations beginning in February 2014.

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REFERENCES

[1] W. Fischer, et al, "Status of head-on beam-beam compensation in RHIC" , proceedings of the ICFA Mini-Workshop on Beam-Beam Effects in Hadron Colliders (BB3013), CERN (2013).

[2] A. Pikin, W. Fischer, et al, “Structure and Design of the Electron Lens for RHIC”, PAC11, New York, NY, USA

[3] Solid Sealing Technology, 44 Dalliba Ave, Watervliet, NY, USA, www.solidsealing.com

[4] Barth Electronics, 1589 Foothill Dr., Boulder City, NV, USA, www.barthelectronics.com

[5] Eurofarad, 93 rue Oberkampf, Paris, FRANCE, www.eurofarad.com

[6] Dearborn Electronics, 1221 N Us Hwy 17 92, Longwood, FL, USA, www.dearbornelectronics.com

[7] Capacitor Industries, 6455 N. Avondale Ave., Chicago, IL, USA, www.capacitorindustries.com