Fast scanning diamond detector for electron beam profile monitoring

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Introduction

Recently, novel electron cooling systems for ion beams are being developed at Brookhaven National Laboratory, such as the Low Energy electron Cooling (LEReC) system, the first electron cooler without any magnetization, designed to maximize collision rates at the lowest energies available at the Relativistic Ion Collider (RHIC) [1], and the ongoing Coherent electron Cooling (CeC) Proof off Principle experiment, currently installed in the RHIC tunnel. Efficient electron cooling requires a high quality, high power electron beam with tight parameters (energy and space trajectory). In order to achieve and maintain the required parameters and stability of the electron beam, its parameters have to be continuously monitored and feedback control has to be developed. However, existing detectors are not suitable for invasive profile measurements of powerful continuous wave (CW) electron beams. As a result, the beam profile of these beams is currently monitored in low repetition pulsed mode and assumed to remain the same in CW mode.

The purpose of the current project was to research and develop a minimally invasive multi-strip diamond detector able to measure simultaneously the 2D halo and beam core profile of high intensity CW electron beams, including those of FELs. Diamond's unique combination of material properties: low energy absorption, tremendous radiation tolerance, ability to dissipate significant heat load, and stability of electronic properties over a wide temperature range, makes it an ideal material for high energy applications. The suggested diamond profile detector is expected to represent a significant improvement over common wire scanners which have a rather short life-time. Their very thin wires are easily overheated and burned, thus contaminating the beam pipe with debris.

The first prototype of a fast scanning diamond beam profile detector (DBPD) suitable for minimally invasive high power CW electron beam core profile measurements in transmittance mode has been developed and fabricated. Its research and development in significant degree was focused on future installation into the high power CeC and LEReC beam-lines at BNL and the detector design was tailored to the corresponding BNL requirements. Numerical modeling demonstrated that the DBPD prototype is suitable for direct core beam profile measurements of the powerful CW mode CeC and LEReC beamlines. The DBPD prototype has been tested at the ATF and CeC electron beamlines at BNL.

Mechanical Design

The mechanical design of the DBPD is shown in Figure 1 and includes: a vacuum chamber consisting of a 6″ cube, reducing nipples, a high speed actuator, and a front optical window for potential installation of an optical pyrometer and luminescence detector. Fast and precise scanning of the diamond required a special high speed actuator having a speed of up to 1 m/s and position precision of about 5 um. Existing pneumatic actuators may provide the required high speed, but they lack speed stability, positioning accuracy and reproducibility. We used the 1 m/s hard shaft motor driven actuator with bellows developed by Ultra High Vacuum Design. Testing of the actuator at UHV-D, see Figure 2, demonstrated good constant speed over 60 mm travel, only 0.42% speed variation at 1 m/s, and good repeatability. The actuator was equipped with a custom feedthrough with an embedded Cu rod and 12 SMB coaxial connectors (made by KJL). In the initial position the diamond sensor is fully retracted from the beam pipe and at the lowest travel position is fully inserted into the beam core near the center of cube, see Figure 1.

The diamond sensor consisted of a 48x19x0.15 mm detector-grade polycrystalline diamond plate (PCD) with embedded 10 vertical and one horizontal conductive strip-lines. Highly B^+-doped CVD diamond layers were grown on both sides of the intrinsic PCD plate. Then, on one side the boron layer was masked and RIE/ICP etched to form the strip-lines. The PCD plate was then brazed to a tungsten carbide support attached to the Cu rod (19 mm diameter, 20 cm long). The massive Cu rod provided a good heat sink for the thin diamond sensor.

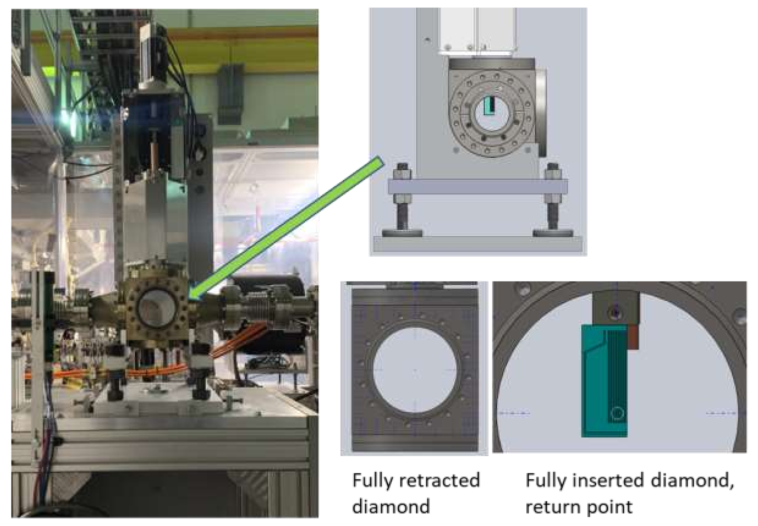


Figure 1. Diamond detector assembly and its schematics.

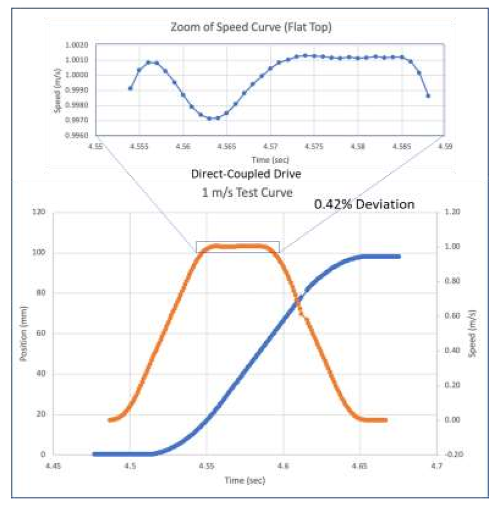


Figure 2. Speed test of fast actuator at UHV-D

Numerical Modeling

I. Thermal impact from high power CW electron beams

Numerical modeling of the thermal impact on the diamond sensor from high power CW beams was performed on a 3D mechanical model, see Figure 3, with ANSYS 2020 R1 software. The geometry of the diamond sensor was modeled with a fine element mesh (total 14,728 elements, comprised of 100,856 nodes). The modeling was performed for a number of cases: CeC and LEReC beams, normal and 45° tilted position of the diamond plate to the beam, static position and motion, and two types of metal substrates supporting the diamond sensor. Electron beam parameters and calculated absorbed beam energy are presented in Table 1, and material properties used in modeling are presented in Table 2.

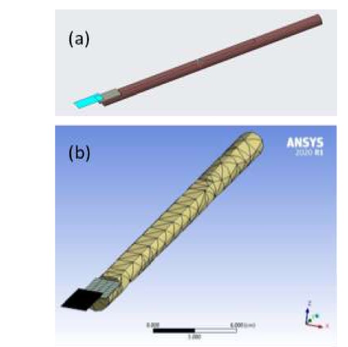


Figure 3. Geometry of diamond sensor brazed to the WC-Co and mounted on Cu rod (a) and its fine element mesh (b).

Table 1. Electron beam parameters used in modeling.

	Diamond thickness (µm)	Electron Energy (MeV)	dE/dx (MeV cm²/g)	Beam current (µA)	Beam σ_x (mm)	Beam σ_y (mm)	Max absorbed power density (W/cm²)
CeC	100	15	1.741	78	3	3	8.38
LEReC	100	2	1.568	35500	2.64	8.55	95

Table 2. Material properties used in modeling

Material	Thermal Conductivity (W/m-K)	Density (kg/m³)	Specific Heat (J/kg-K
CVD PCD	1200	3515	502
WC-Co	49.6	15600	183
Copper	401	8300	385

CeC Beam

Thermal modeling of a stationary and moving diamond sensor was performed for CeC beam, see Figure 3 for geometry and Figure 6c motion profile, corresponding to the maximum 1 m/s actuator speed and the stroke of 45 mm. Ambient temperature (25 C) was placed at the end of the copper rod further from detector. In stationary position sensor doesn't move and beam is turned on at zero time.

No sensor motion. Sensor was fully inserted into the beam, normal sensor orientation. Temperature map is shown in Figure 4 at 0.127 s and for the achieved steady state. The corresponding time dependence of the maximum temperature is shown in Figure 5. The steady state condition with maximum temperature of about 100 °C is reached at about 20 s.

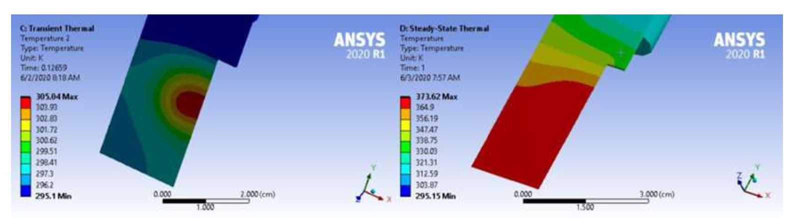


Figure 4. Temperature profile at 0.127 s after the beam was turned on (left) and final steady state (right).

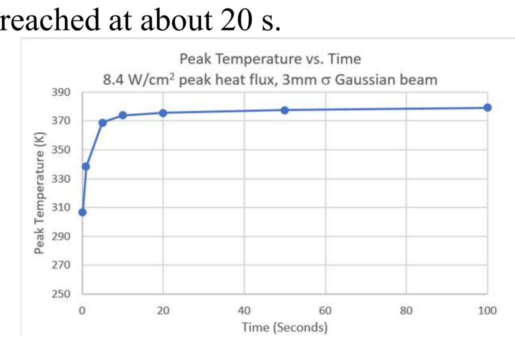


Figure 5. Peak temperature time dependence after the beam was turned on.

Sensor motion. Stationary beam, normal sensor orientation. The transient maximum temperature is shown in Figure 6. The maximum temperature of 30 °C occurs at about 40 ms and then within several seconds return to the ambient.

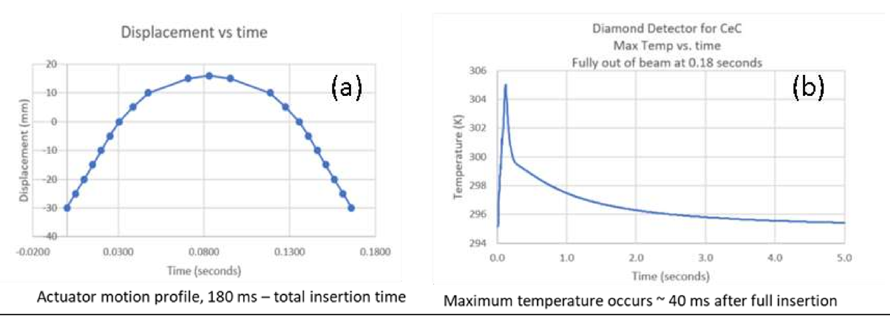


Figure 6. CeC beam, transient state with sensor motion. (a) motion profile of diamond sensor used in temperature modeling, (b) maximum temperature of diamond for the motion profile on the left

LEReC Beam

Sensor motion. Stationary beam, normal sensor orientation, motion profile same as for CeC (see Figure 6a). The temperature map at short times is shown in Figure 7 and the time dependence of maximum temperature is shown in Figure 8. The maximum temperature of about 370 °C occurs at about 140 ms and then similarly to CeC returns to the ambient within 5 seconds.

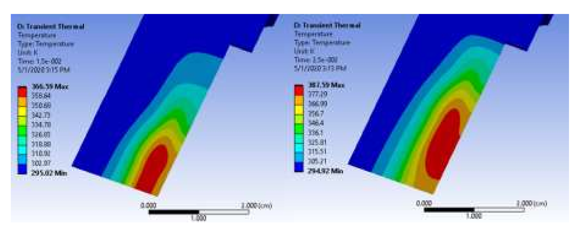


Figure 7. LEReC beam, transient state with sensor motion. Left – insertion time 15 ms, right – 25 ms.

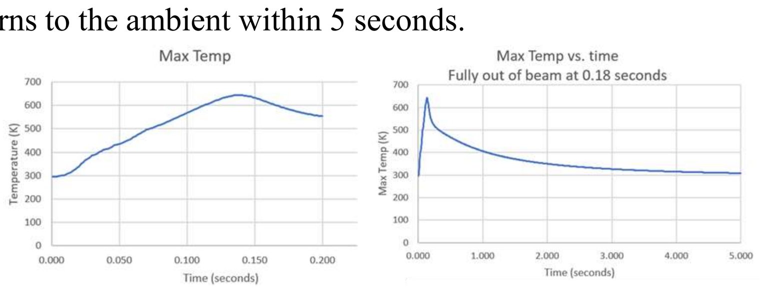


Figure 8. LEReC beam, transient state with sensor motion. Maximum temperature of diamond sensor for the motion profile on Figure 5a.

Thermal impact modeling results

- For the 78 uA CW CeC beam, the steady state condition with a maximum temperature of about 100 °C is reached at about 10-20 sec after the beam is turned on and after that the temperature doesn't change at least during the first 2 minutes. The maximum steady state temperature for a 45° tilted sensor was about 17 °C higher.
- At the maximum actuator speed, the total insertion/removal time of the sensor could be as small as 180 ms. In this case the maximum temperature of 30 °C occurs at about 40 ms and then returns to the ambient within several seconds.
- The replacement of the tungsten carbide support substrate to a copper substrate results in a small decrease of temperature by about 10 °C.
- For the 35.5 mA CW LEReC beam, at the maximum actuator speed the maximum temperature of about 370 °C occurs at about 140 ms and then, similarly to the CeC, returns to the ambient within 5 seconds.

II. Electrical response and effect of ferrite addition

The vacuum chamber electrical response to the CeC beam was modeled using Particle Studio for the cases with and without additional ferrite installed into the vacuum chamber. The results are shown on Figure 8 and demonstrate that even one ferrite is very effective in attenuating the oscillations. The oscillations are not the wake field but the electrical oscillations of the sample holder. If the bunch frequency is 78 kHz, there is enough time for these oscillations to decay before the next bunch arrives, even without the ferrite.

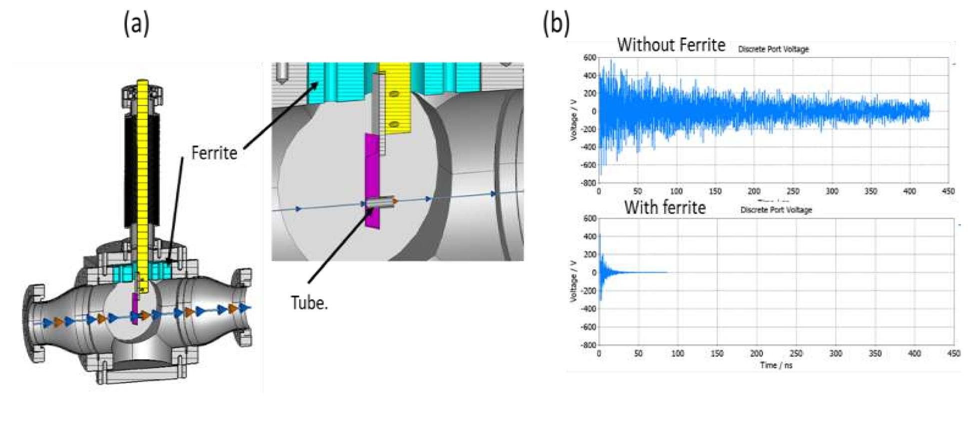
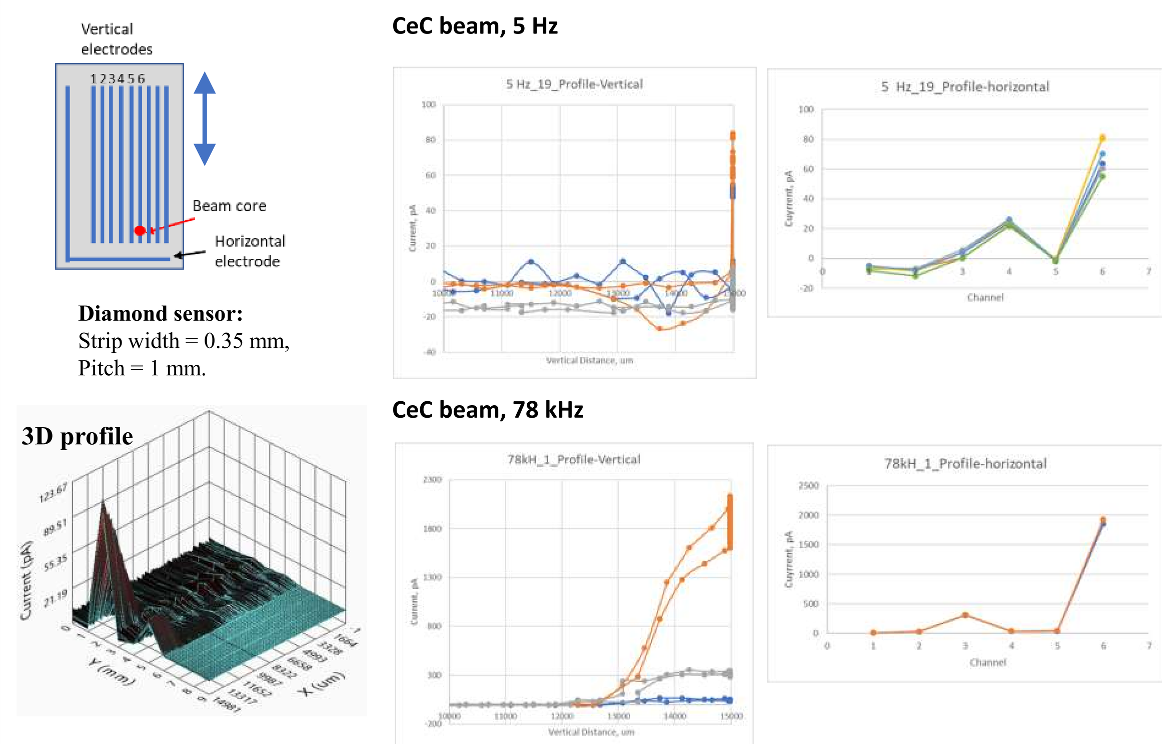


Figure 9. Particle Studio simulation of the electrical response for the diamond detector system. (a) 3D model of detector system, tube was used to simulate the interaction of the beam with the target; (b) Detector voltage plots with respect to ground for 5 nC, 100 ps FWHM bunches, with and without ferrite. .

Experimental Results

CeC Beam Testing

- CeC beam: 30 pC per bunch, 5 and 78 kHz repetition rates.
- Diamond sensor was moved into the beam pipe line from a fully retracted position, inserted into the beam core for 20 sec, and retracted back.
- Digital electrometers used for transient current measurements (2 x F460, 16 bit, 250 kHz, Pyramid Tech. Cons.) were not synchronized with electron beam pulses which resulted in multiple missed pulses. Acquisition time constant of the electrometers was 0.1 s. Electrical bias of the diamond sensor was 0 V, diamond thickness was 150 um. Vertical distance was measured from the diamond sensor homing position (fully retracted from the pipe).



- The diamond detector was fully operational under its full insertion into the 78 kHz CW CeC beam core for up to 20 sec.
- Transient currents (up to 2000 pA) were detected from the horizontal electrode and <u>all six</u> vertical electrodes.
- The vertical beam profile at 78 kHz shows an approximately 3 mm wide core. The narrow vertical beam profile at 5 Hz may be related to low signal intensities and poor signal synchronization.
- The horizontal beam profile demonstrates "double beam cores" which is rather unusual. It could be the result of "dead" pixels or poor signal synchronization.

Conclusions

- **The first prototype of a fast scanning diamond beam profile detector suitable for minimally invasive high power CW electron beam core profile measurements in transmittance mode was developed and successfully tested with pulsed (5 Hz) and CW (78 kHz) CeC beams.**
- **Thermal modeling demonstrated a manageable thermal impact even from a relatively long (up to 2 min) insertion of the diamond sensor into the 78 µA CW CeC beam core.**
- **Thermal modeling demonstrated a manageable thermal impact from a very short insertion (about 200 ms) of the diamond sensor into the 35.5 mA CW LEReC beam core.**
- **Electrical impedance modeling of the detector and vacuum chamber assembly demonstrated minimal impact on beam line impedance with diamond sensor insertion.**
- **Transient currents from the multi-strip diamond detector were measured with fast digitizing electrometers and XY beam profile was obtained.**

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