Fermilab LDRD Proposal

Project Title: Thin sCVD Diamond Halo / Loss Monitor

Principal Investigator: Arden Ayube Warner
Lead Division/Sector/Section: AD/APC
Co-Investigators (w/institutions): (if applicable)

Proposed FY and Total Budgets: (summary of budget page (in dollars))

	SWF	SWF OH	M&S	M&S OH	Contingency	Total
FY14						
FY15	**$35.1k**	**$29.9k**	**$43k**	**$10.1k**		**$118.1k**
FY16	**$25.8k**	**$22k**	**$42k**	**$9.9k**		**$99.7k**
Total	**$60.9k**	**$51.9k**	**$85k**	**$20k**		**217.8k**

SWF: Salary, Wages, Fringe SWF OH: overhead on SWF
M&S: Material and Supplies M&S OH: overhead on M&S
Contingency (estimate of additional funds that might be required with justification)

Initiative: 2015 Broad Scope
Project Description

The objective is to design, build and test a robust particle detector that works in a wide range of particle beam energies and fluxes. The proposed detector will be designed using uncharacteristically thin (< 100 μm), single crystal Chemical Vapor Deposited (sCVD) diamond structures with an open-design concept. This is a novel approach that also implements a method for RF noise rejection in an accelerator environment. The concept we will describe holds several advantages over silicon and polycrystalline structures and offers a wider dynamic range and linearity than standard loss monitors. This technology also advances the state of the art in terms of temporal response. Diamond crystals have the added advantage of being capable of both room temperature and cryogenic operation inside the vacuum system. Possible accelerator applications will include monitoring of beam halo development and measurement of beam loss at low energies as in the case of protons with energies < 10 MeV. In this case, particles do not escape the vacuum chamber but can induce losses that are typically capable of damaging and/or quenching cryogenic systems. In these regimes traditional beam loss monitors do not work and lack the sensitivity, dynamic range, temporal response and radiation hardness of the detector being proposed. In addition, this concept provides a device that has the potential of single particle detection, an effective diagnostic for beam extinction measurements. It also pushes the envelope on thin diamond development by using a new deposition substrate and technique.

Significance

Several planned and operating accelerator facilities that produce intense particle beams are also typically designed with superconducting accelerating structures that can be affected by low energy beam losses at injection stages and with beam halo issues at later stages. Understanding and controlling beam halo and detecting low energy losses is thus important for these high-intensity hadron accelerators, for high-brightness electron linacs, and for low-emittance light sources. Direct monitoring of the development of the halo mechanism and measurements of the associated losses requires diagnostics which are minimally invasive with high dynamic ranges, high sensitivity and good temporal response needed to observe the halo in the presence of an intense core. Fermilab's PIP-II and IOTA/ASTA are examples. The state of the art methods for detecting and monitoring lower energy losses (< 10 MeV) or for characterizing beam halo development which can induce beam loss are limited either by dynamic range, temporal response, sensitivity or some combination of these effects. Present techniques utilize scrapers, wires, optical methods (OTR etc.) and noninvasive techniques such as ionization profile monitors and back scattered electrons. These methods produce dynamic ranges from 10^4 up to 10^8 with varying sensitivities and temporal responses [1][2]. Never-the-less, at very low energies, hadron beam losses are notoriously difficult to measure and are outside the range and scope of the standard loss monitoring.

General background

Chemical Vapor Deposition (CVD) diamonds are readily available commercially and are radiation hard semiconductor devices. The advent of single-crystal (sCVD) and poly-crystalline (pCVD) structures has made it possible to provide detector material with precise shapes and uniform properties suitable for loss monitor detection in particle accelerators. Advanced electronics has allowed for the pico-second structure of the diamond response to be fully exploited and provides the elements needed for an extremely wide range of high energy particle detectors. Current interest in beam halo development, single particle proton detection (required for extinction measurements), low energy proton loss monitoring in accelerators where intense beams are injected from warm injector front-end accelerators into superconducting RF structures (PIP-II, SNS etc.) and future accelerator applications render these materials worthwhile for diagnostics test.

Proposal

We are proposing to design, build and test an ultra-thin single crystal diamond detector for measuring low energy beam loss inside the vacuum system and for characterizing beam halo development by incorporating the crystal into a scraper type device. This diagnostics instrumentation approach is innovative with respect to the application of diamond detectors to low-energetic protons. The detector design will consider several characteristics. The protons must traverse the diamond in order to avoid pile-up; therefore the detector must be extremely thin. There must not be any material before the sensing electrode; therefore an open structure is necessary. For noise immunity a dedicated technology will be employed that avoids RF pick-up from the accelerator. These techniques are novel and have never been used for fast beam loss measurements. We plan to also exploit the facts that diamond is proven to be linear in its ionization behavior from 1MIP to 1e^9 MIPS per pulse and that the fast time response of diamond (14.6 ps) is dependent on noise level, the amplitude of the signal and the rise time of the signal [4]. Moreover we choose thin single-crystal diamonds over poly-crystal diamonds to take advantage of the factor of 3 or 4 greater charge yield offered by single-crystal structures. For example, as shown in Figure 1 the charge generated is detectable over a wide range of proton energies. Thin poly-crystals < 100 microns have the disadvantage of being blind at certain position/angles due to grain structure.

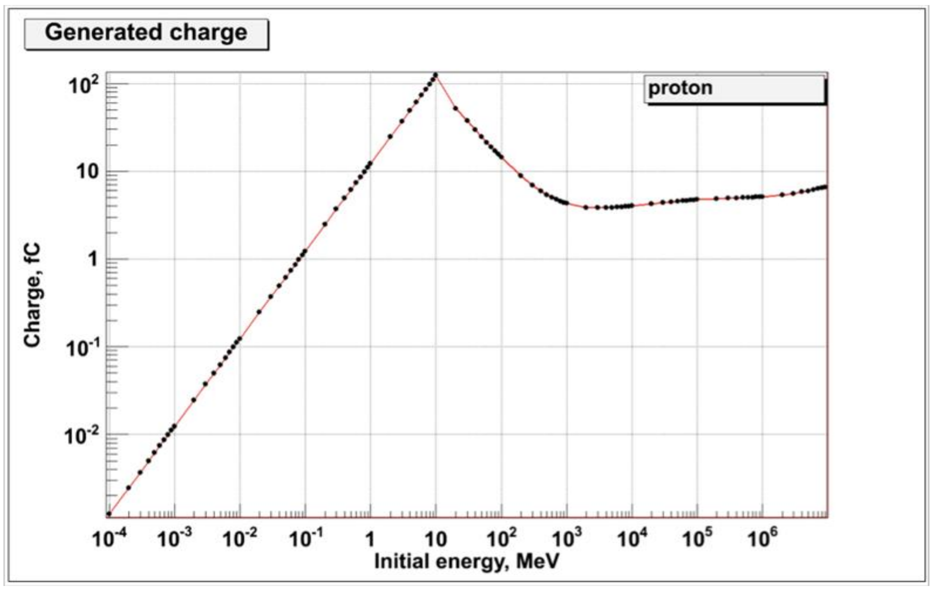

Figure 1: Plot of charge versus proton beam energy.

Advantages over silicon and other devices

Other materials can be considered since thin silicon diodes exist. However, diamonds do not require doping (no PIN-Structure), are simple to handle, and are very robust in operation. This is a big advantage, in particular for thin structures. The radiation hardness of diamond is also a factor (and is much better than silicon), and this increases the lifetime of the final product. Diamond is also light insensitive and temperature insensitive; the former is advantageous during lab tests, and the latter is an advantage over silicon diodes, which have an exponential dependence on temperature. This makes it more difficult to use as a standard instrumentation device. Finally diamond crystals have been demonstrated to work at cryogenic and room temperatures. Silicon is however not known to operate at cryogenic temperatures. Diamond is more robust and this is why we are pursuing this approach. Table1 shows additional properties of diamond compared to silicon and highlight’s some of the advantages and disadvantages of both.

Table 1: Summary of some fundamental properties of diamond vs silicon

Property	Diamond	Silicon	Advantage
Band gap [eV]	5.5	1.12	Low leakage
Breakdown field [V/cm]	10^7	$3 \cdot 10^5$	
Intrinsic resistivity @ R.T. [Ω cm]	$> 10^{11}$	$2.3 \cdot 10^5$	
Intrinsic carrier density [cm^{-3}]	$< 10^3$	$1.5 \cdot 10^{1}0$	
Electron mobility [cm^2/Vs]	1900	1350	
Hole mobility [cm^2/Vs]	2300	480	
Saturation velocity [cm/s]	e^-: $0.9 \cdot 10^7$ holes: $1.4 \cdot 10^7$	$0.82 \cdot 10^7$	
Density [g/cm^3]	3.52	2.33	
Atomic number - Z	6	14	
Dielectric constant - ε	5.7	11.9	Low capacitance
Displacement energy [eV/atom]	43	13-20	Radiation hard
Thermal conductivity [W/m.K]	≈ 2000	150	Heat spreader
Energy to create e-h pair [eV]	13	3.61	
Radiation length [cm]	12.2	9.36	
Interaction length [cm]	24.5	45.5	
Spec. Ionization Loss [MeV/cm]	6.07	3.21	
Aver. Signal Created / 100 μm [e_0]	3602	8892	Low signal, Low Noise
Aver. Signal Created / 0.1 X0 [e_0]	4401	8323	

Research Plan

The plan is to design the detector hardware in several stages commensurate with the developmental results associated with the manufacturing of the thin sCVD diamonds.
In order to achieve the thinnest diamonds possible we plan to employ a new deposition technique where the CVD process is done on graphene-like substrates. This has shown adequate progress and produces thin diamonds with higher tensile strengths than previously achieved. In stage 1 (first year) non-beam and beam-related test will be conducted outside of the vacuum with the diamond to evaluate its specification and verify that the quality is adequate to proceed. Table 2 lists the parameter/requirements that we plan to achieve with the first prototype diamond:

Table 2: Planned parameters for the first prototype detector.

Parameter	Value/type	Units
sCVD thickness	150	µm
Detector capacitance	3	pF
Bias voltage	100-150	volts
Bias voltage cycle rate	15	Hz
Substrate size	4 x 4	mm
Electrodes	Single pad, gold 3x3	mm
PCB Structure	FR4 epoxy	n/a
Charge amplifier gain	4.4	mV/fC

This first hardware prototype which is already more than a factor of 3 times thinner than standard production devices will be tested and verified at room temperature. The design will include an open detector structure where the surface of the electrode will directly face the beam. It will be a compact structure with a single connector for bias voltage and signal readout of the diamond detector. At this stage the following will be verified:

a) Robustness of the detector layout
b) Signal integrity
c) Quality of RF avoidance method
d) Readout electronics
e) Vacuum compatibility and mounting
f) Calibration and signal-to-noise ratio
g) Cyclic bias voltage test

The impulse responses of the charge amplifier and the instrumentation amplifiers to be used with the device will also be tested and can in principal be done at the ASTA facility. Initially oscilloscope displays of the data will be sufficient to verify the full performance of this first stage device outside of vacuum. The final verification of this particular device can be done in the planned diagnostics section of PXIE with low energy protons.

In the second and final proposal year we will procure our thinnest diamonds of 75 and 25 microns with the specifications listed in Table 3. They will undergo similar verification tests, but they will also be tested with beam at PXIE and/or IOTA/ASTA facilities. These devices will be edge mounted in preparation for a mechanical-scraper-design application. Vacuum compatibility and mechanical designs will be developed for the device.

Table 3: Planned parameters for the second prototype detector.

Parameter	**Value/type**	**Units**
sCVD thickness	75/25	μm
Detector capacitance	3	pF
Bias voltage	< 50	volts
Bias voltage cycle rate	15	Hz
Substrate size	5 x 5	mm
Electrodes	Single pad, gold 3x3	mm
PCB Structure	Vacuum compatible	n/a
Charge amplifier gain	4.4	mV/fC

The following is part of the work required to complete the detector prior to designing the appropriate mechanical housing for beam test.

- Solve signal read-out issues.
- Preparation of detector layout.
- PCB prototype (4-layer structure). Manufacture issue.
- Gluing and bonding with RF-protection. Manufacture issue.
- Detector assembly.
- Lab test and documentation

Successful developments and assembly of the detector, electronics and vacuum mechanicals would be a significant step forward. A final stage device with a 25 μm diamond structure with readout electronics will be constructed.

Deliverables year 1:

- Two of the thinnest single crystal diamond detector ever achieved, with open electrode structure and RF protection
- A vacuum compatible detector built for test with low energy beam.

Deliverables year 2:
A 25 micron prototype loss monitor appropriately shaped and mechanically mounted as a complete instrument for beam testing. Documented sensitivity, dynamic range and temporal response.

Beam Testing
Several possible opportunities for beam test exist at Fermilab in the second year of this proposal when it is believed that the characteristics of the detector layout would have been verified. In addition, other facilities have indicated interest in this research and testing possibilities exist at these locations. A successful detector would produce a clear indication of very low energy beam loss well correlated with beam intensity, a single particle measurement quantifiable with electronic calibration signals, and a promising prospect for halo measurements if configured correctly.

Future Funding

Low energy, high resolution loss measurements are of interest to many accelerator based applications but they are not many direct methods under study with the potential characteristics described. If these LDRD supported experiments work, one can expect PIP-II funds to instrument the future accelerator with sCVD detectors. Successful results will also apply to the ASTA/IOTA injector and possibly the IOTA ring using either electrons or protons.
Also note that advice from the final summary report from the 2nd meeting of the XMAC (PIP-II Machine Advisory Committee, Feb 25th -26th, 2014 Fermilab) stated the following: “The monitoring of beam loss at low energy is important and notoriously difficult. The committee strongly supports the R&D on CVD diamonds beam loss detectors”.
The result from this developmental process as well as the beam based measurement would be publishable in Nuclear Instruments and Methods. Work may also be of interest to the beam instrumentation community.

References

[1] K. Wittenburg, Overview of recent halo diagnosis and non-destructive beam profile monitoring, 39th ICFA Advanced Beam Dynamics Workshop on High Intensity High Brightness Hadron Beams, HB2006, Tsukuba, Japan, 2006, e-proceedings (JACoW), pp. 54–8.

[2] P. L. Colestock, et. al., "The Beam Halo Experiment at LEDA", LINAC2000, Aug. 21-25, 2000, Monterey, CA
[3] T.P. Wangler et al., Beam halo in proton linac beams, 10th International Linac Conference, Linac 2000, Monterey, CA, 2000, e-proceedings (JACoW), pp. 341–5.
[4] PhD thesis Hendrik Jansen: Chemical Vapour Deposition Diamond, University of Bonn, Germany, 2013.