Jefferson Lab
Thomas Jefferson National Accelerator Facility
Exploring the Nature of Matter

LABORATORY DIRECTED RESEARCH AND DEVELOPMENT PROPOSAL

TITLE: BEAMLINE FOR E-BEAM PROCESSING AT UITF

TOPIC: DEVELOPMENT OF TECHNOLOGIES FOR THE APPLICATION OF PARTICLE BEAMS

LEAD SCIENTIST OR ENGINEER:	FAY HANNON
Phone:	X 6434
Email:	fhannon@jlab.org
Date:	5/17/19
Department/Division:	Accelerator/SRF Institute
Other Personnel:	Gianluigi Ciovati
Proposal Term:	**From:** 10/2019 **Through:** 10/2021 **If continuation, indicate year (2nd/3rd)**:

Division Budget Analyst	Kelly Webster
Phone:	X 7575
Email:	Hanifan@jlab.org

Abstract

The proposed project aims at establishing a beamline in the UITF which can be used to perform irradiation studies of materials using an electron beam with an energy of up to 10 MeV. The design aspects will include the beam transport simulations, and the engineering of the target holder. All the components required to complete the beamline will be procured and installed. The first application will involve irradiation of wastewater samples in collaboration with Hampton Roads Sanitation District.

1.0 Summary of Proposal

1.1 Description of Project

The research program focuses on the following tasks:

- Design of an experimental beamline at the UITF through beam dynamics simulations
- Design of the water sample target (including electron window interface, multiple sample carousel and expected dose)
- Beamline and target manufacture and construction
- Beamline commissioning with electron beam
- Safety analysis
- Water sample irradiation

The project consists of the design, commissioning and testing of a diagnostic beamline at the UITF and of a target station to allow irradiation studies of materials using a low-power electron beam of up to 10 MeV of energy.

A titanium-foil window will be used at the beam exit point to separate the beamline vacuum from outside environment. The design phase will consist of beam transport simulations to determine the location of beam focusing elements along the beam line and for enlarging the beam at the exit window to achieve a uniform distribution over the sample area.

A multiple-target holder will also be designed as part of the project, in order to be able to irradiate multiple samples without need for multiple accesses into the UITF beam enclosure. The components required for the beamline installation such as quadrupoles, beam exit window, fast-closing valve will be procured and installed.

Experiments will be conducted on wastewater samples provided by Hampton Roads Sanitation District (HRSD). HRSD will conduct the analysis of the samples pre- and post-irradiation as an in-kind contribution.

The proposed project would provide a training opportunity for a graduate student in accelerator science and technology and it would be a stepping stone towards promoting the industrial application of accelerator technology. The proposed project will also enhance the laboratory's technical facilities and foster collaboration with local industrial partners.

1.2 Expected Results

A functional beamline which provides electron-beam irradiation source with up to 10 MeV of energy is expected as a result of this project. This irradiation source can be used to evaluate the possibility of reducing contaminants in wastewater that cannot be easily broken down by current technologies and also to study the potential benefits of e-beam irradiation to various other materials.

2.0 Proposal Narrative

Electron beam irradiation has several industrial applications such as the cross-linking, curing and polymerization of plastics, treatment of flue gases and wastewater, sterilization, color enhancement in gemstones, treatment of asphalt [1]. In most cases, the main limitations towards a wider use of electron-beam irradiation are the reliability and cost of the accelerator. The treatment cost can be reduced by increasing the beam power. Jefferson Lab has been recently involved with the design of both superconducting and normal-conducting high-power (200 kW-1 MW) CW electron accelerators of 0.5 – 2 MeV energy range for environmental remediation [2].

In particular, electron beam irradiation is an attractive technology for the treatment of municipal wastewater or contaminated water from industrial sites. For example, the development of fracking for oil and gas has produced large volumes of heavily contaminated water which is currently being stored in huge ponds. Growing challenges for municipal wastewater treatment are represented by the growing number of residuals from pharmaceutical and personal care products and from perfluoroalkyl substances, which are chemicals present in a variety of household products [3].

HRSD is interested in evaluating the benefit of electron-beam irradiation to reduce the concentration of some of these chemicals, beginning with 1,4-dioxane for which HRSD already has dedicated analytical instrumentation capabilities.

2.1 Purpose/Goals

The purpose of the proposed project is to design, install, commission and operate a beamline of the UITF to provide an electron beam irradiation source to study the effect of different doses on materials.

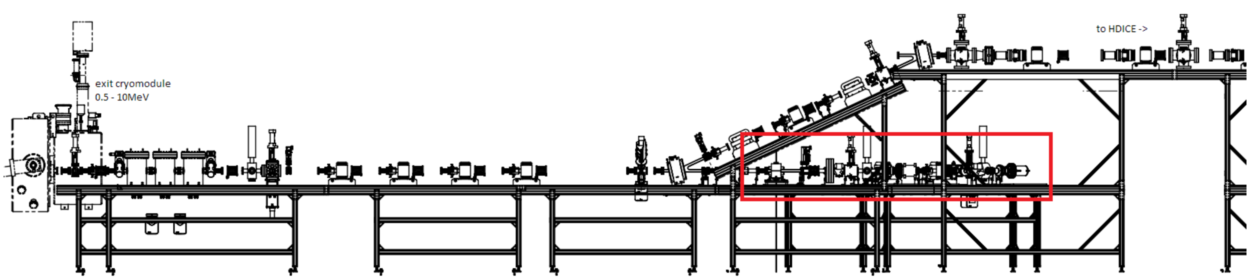
The short-term goal of such irradiation source is to study the benefits of e-beam irradiation towards the remediation of wastewater, through the interest and support of HRSD.

2.2 Approach/Methods

The UITF is capable of providing a CW electron beam of energy up to 10 MeV and 100 nA of current. The beamline shown in Fig. 1 is currently used to send the beam to a dump and it is the one which would be modified for the proposed project.

A schematic diagram of the beamline components is shown in Fig. 2. The electron beam propagates from left to right. First a fast valve is placed as far upstream as possible to protect the cryounit from any potential vacuum failures in the system. A typical diagnostic 6” cross will be installed to quantify the electron beam quality at the entrance of the water test beamline. A quadrupole triplet will be utilized to generate a large transverse, round electron beam that will pass through a thin-foil window, which separates the high beamline vacuum from the air side. A final diagnostic cross will be used for alignment and as a vacuum trigger should the window fail. Two sets of beam steering magnets will be placed before and after the quadrupole triplet to control the beam position. The overall length of the beamline will be determined based on beam transport simulations.

The 50 μm thick Ti window is a demountable foil held in a 6” Conflat flange (Part FWFSS-0600, Atlas Technologies). A sample carousel that can hold multiple samples at a time will be designed and built. The samples’ area will be surrounded by local radiation shielding.



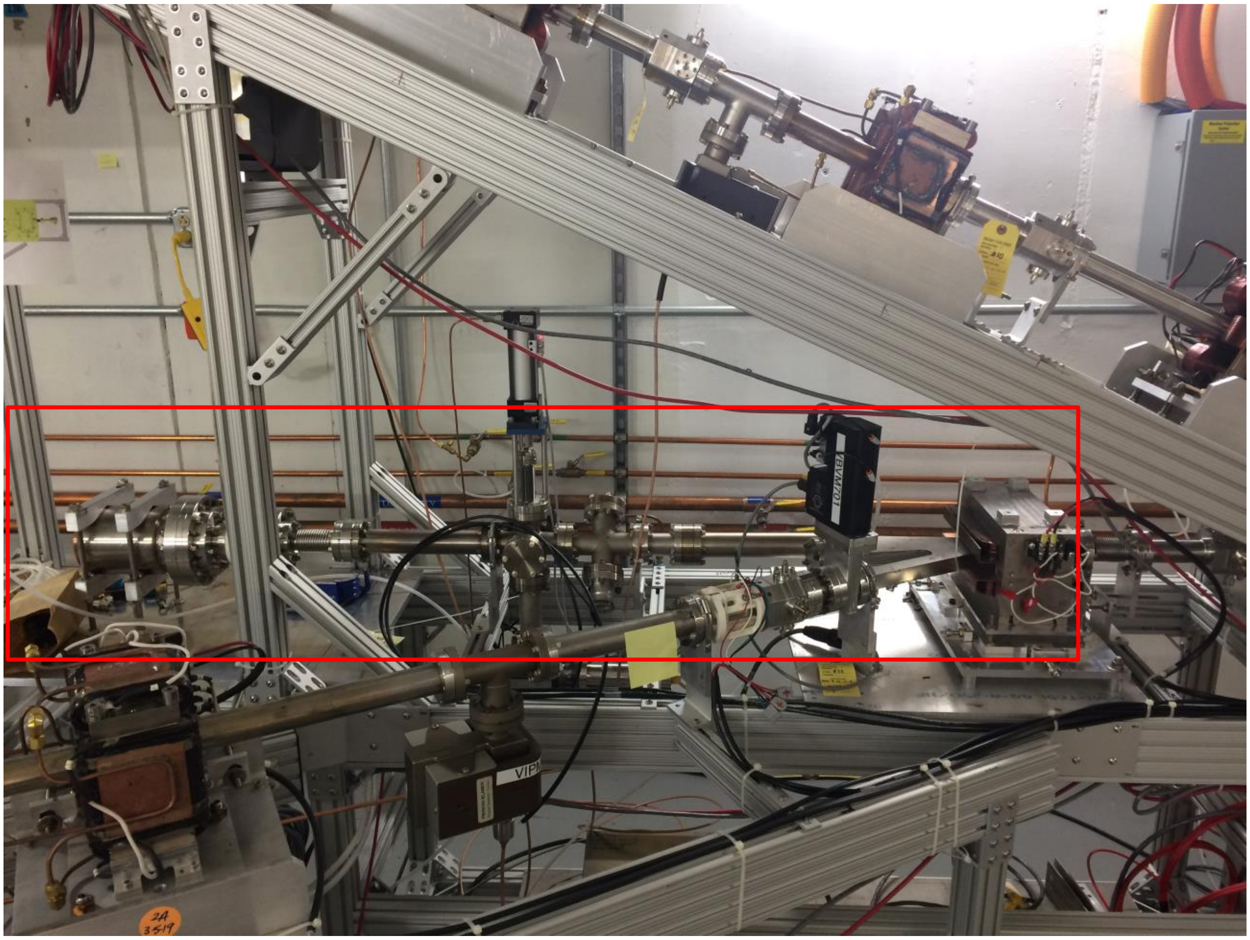


Figure 1: (Top) MeV region of UITF. The straight-ahead beamline dump would be modified (red box). (Bottom) Image of the beamline to be modified.

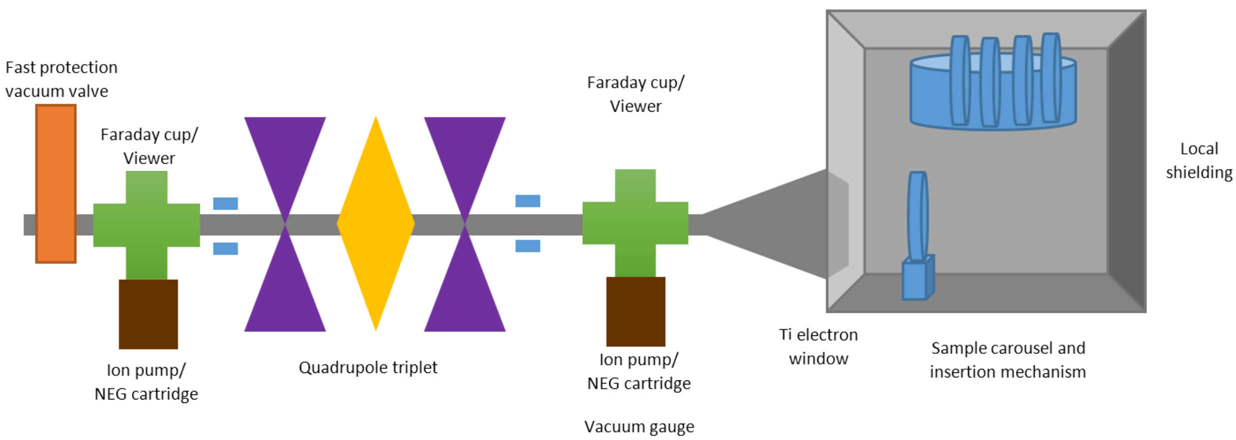


Figure 2: Conceptual beamline design.

As the electron beam travelling through air results in the production of ozone, it must be verified that the ozone concentration is kept below the human threshold limit value (TLV) of 100 ppb. The ozone concentration by weight can be calculated using the following equation [4]:

$$\text{Ozone conc.} = 1.24 \times 10^{-6}\ P_{air}\ (\text{W})/F\ (\text{m}^3/\text{min}) \qquad (1)$$

where P_{air} is the beam power loss in air and F is the air exhaust rate, which is 11800 CFM in the UITF. The beam power loss in air can be calculated as:

$$P_{air} = \text{LET}\ \rho\ d\ I_{beam} \qquad (2)$$

where LET is the total stopping power (also called "linear energy transfer") for air, ρ = 1.2 kg/m^3 is the density of air at 20 °C, 1 atm, d is the distance the beam travels in air and I_{beam} is the beam current. LET for 10 MeV electrons in air is 2.16 MeV cm^2/g [5]. For d = 5 cm and I_{beam} = 100 nA, the ozone concentration calculated with Eq. (1) is 5 ppb, well below the TLV. The maximum beam current that results in an ozone concentration of less than 100 ppb is 2 μA, for d = 5 cm. It should also be mentioned that administrative and engineering controls are in place to prevent any personnel to be inside the UITF vault during beam operation, making the exposure of personnel to ozone extremely unlikely. Detailed simulations of the electrons' energy loss through the exit window, the air space and the sample will be carried out using Monte Carlo codes such as FLUKA [6].

One design aspect of the project is related to the area of the beam exiting the window in order to assure a power density sufficiently low to avoid the risk of rupture of the window and to assure a uniform dose over the sample volume. Beam exit windows made of 50 μm-thick Ti foil with forced air cooling can sustain an electron current density of the order of up to ~100 mA/cm^2 [7]. Given that the expected beam current from the UITF is 100 nA, a beam diameter of 1 cm would result in a current density about six order of magnitude lower than the value mentioned above. A thermal and mechanical finite-element analysis of the exit window will be carried out to verify that no additional cooling of the window is required, given the current density required to irradiate the sample.

In the case of any unforeseen possible issues related to the sample to be irradiated being in air which could emerge during the design phase of the project, a backup solution will be to place the samples in a vacuum chamber maintained at ~10^{-3} mbar by a scroll-pump.

Figure 3 shows a plot of the electron depth of penetration in water (also called "range") as a function of beam energy, in the range 1-10 MeV, expected to be available with the UITF. The typical volume of water sample required for the analysis of 1,4-dioxane ranges between 10-500 ml, depending on the requested detection limit [8]. Figure 4 shows a plot of the diameter of the beam and of the sample's container as a function of beam energy for different volumes of water to be irradiated, assuming a thickness of the sample equal to the electrons' range. We expect the maximum diameter of the beam at the target location to be ~13 cm.

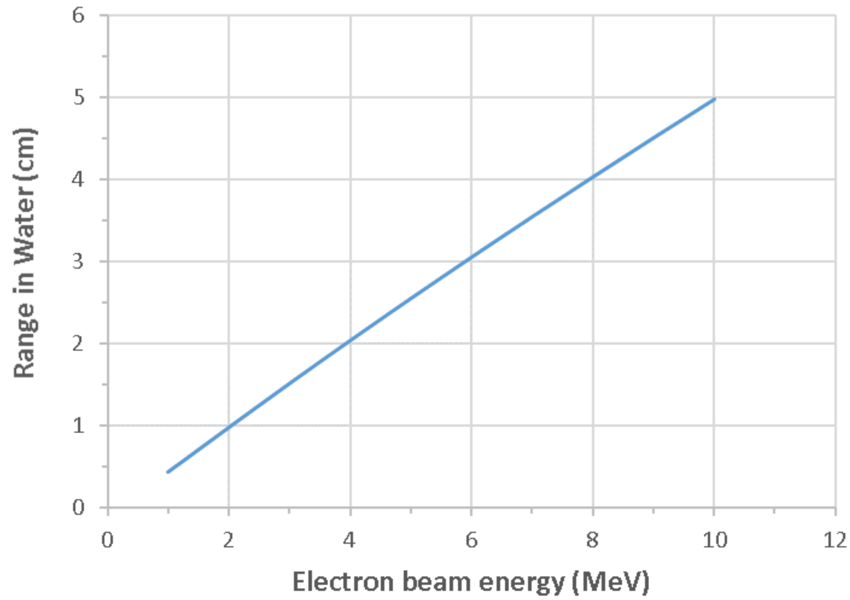


Figure 3: Electrons' range in water as a function of their kinetic energy.

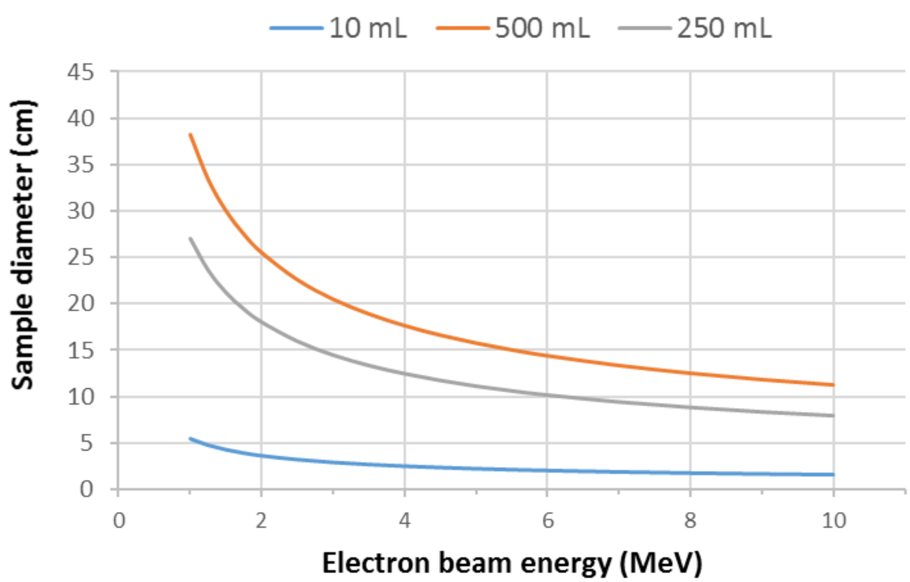


Figure 4: Estimated diameter of the sample as a function of beam energy for different sample volumes.

The experimental runs will consists of irradiating water samples with a contaminant of a known concentration, prepared at HRSD. The concentration of the contaminant will be measured after irradiation and measurements are typically done as a function of the dose. The typical dose range for contaminants in water is 1-10 kGy.

The irradiation time, t, to achieve a certain dose can be calculated as:

$$t\ (\text{sec}) = \text{Dose (kGy)}\ V\ (\text{ml})/(P_{\text{beam}}\ (\text{W})\ \varepsilon) \tag{3}$$

where V is the sample volume, P_{beam} is the beam power and ε is the efficiency of the radiolysis, typically ~70%. Figure 5 shows plots of the irradiation time vs beam energy to achieve different doses, for different sample volumes, assuming a constant beam current of 100 nA. Figure 5(b) shows that a beam energy > 5 MeV is necessary for an irradiation time of less than 2 h to achieve a 10 kGy dose in a sample volume > 100 ml.

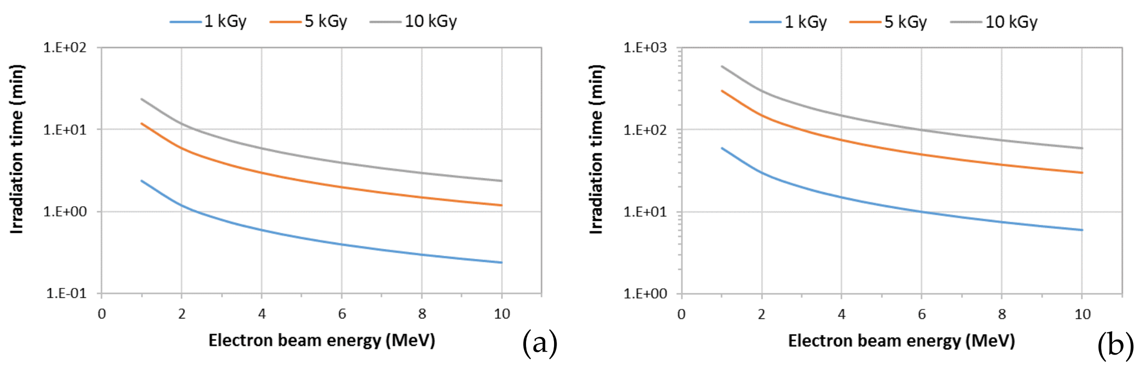


Figure 5: Estimated irradiation time as a function of beam energy to deliver a certain dose to a water sample of 10 ml volume (a) and 250 ml volume (b).

Monte Carlo calculations using FLUKA will be done to optimize the target region and the sample container to assure a uniform dose distribution over the sample volume. The dose delivered to the sample will be measured using radiachromic dosimeter films (FWT-60 series, Far West Technology, Inc.) placed in front of the sample. Jefferson Lab already uses such films and has the readout device for them.

2.3 Resources to be used

The proposed project will require the use of the UITF for the installation of the beamline components and the samples irradiation studies. We anticipate the need to work on the existing beamline beginning in the Fall of 2020 through the Summer of 2021, during planned shutdown periods. The testing of an estimated 20 water samples would require an approximate beam time of about 10 h divided in ten 1-hour intervals in the Fall of 2021.

2.4 Anticipated Outcomes/Results

The outcome of this project would be the availability of a beamline for material irradiation studies. The beamline design and components would be described in a peer-reviewed publication. The proposed project will also serve as an opportunity for a graduate students to be trained in the field of accelerator science and technology.

The first use of the beamline would be to study the effect of dose on reducing the concentration of 1,4-dioxane in wastewater, in collaboration with HRSD, and it would also result in a joint publication.

It should be considered that Jefferson Lab is already working on the development of high-power e-beam accelerators for environmental applications and HRSD has been operating since 2018 a research facility (SWIFT) in which advanced water treatments are used to treat water to a level which allows discharging it back into the aquifer. As a consequence, successful results from studies using the beamline installed through this project and of the industrial accelerators being developed at Jefferson Lab could result in the future in the adoption of the e-beam accelerator technology by HRSD.

3.0 Budget Explanation

The proposed budget includes the following labor allocations:

- Support for a graduate student for the duration of the project. The graduate student will be involved with the beam dynamics simulations, design, procurement and installation of some of the beamline components and operation of the accelerator
- F. Hannon will be mentoring the graduate student, manage the project and will be involved with all the design aspects of the project.
- G. Ciovati will be involved with the advising of the graduate student and the design and procurement of some of the components.
- A computer scientist from the Ops. Dept. will develop the EPICS interface for the beamline components.
- A Radiological Engineer will be involved with the Monte Carlo simulations for the dose distribution.
- A Mechanical Engineer will be involved with the thermal and mechanical analysis of the window.
- An Accelerator Scientist (C. Hernandez-Garcia) will be involved with the operation of the accelerator.

- A mechanical designer will be involved with producing the drawings with the beamline layout.
- An Engineer from the Engineering Division will be involved with the installation of the quadrupoles and their power supplies.
- A Technician from the Engineering Division will be involved with the installation of the control cables for the beamline components.
- The following procurements are expected for the project:
- A fast-close in-line all-metal UHV gate valve to isolate the cryomodule in case of an air leak.
- Three standard quadrupoles, to be fabricated in-house.
- Local shielding for the target region.
- Parts for the sample carousel.
- Ion pump power supply.
- Titanium window assembly.
- Vacuum hardware for the beamline.
- Radiochromic films.
- Machine Shop charges to fabricate components for the sample carousel.
- We would also like to request support for travel within the U.S. to give the opportunity to the student to attend the North American Particle Accelerator Conference.
- We expect to already have the availability of the following components:
- Harps and beam viewers
- Ion pumps
- A manual gate valve

The total budget is $280,449 loaded over two years, with $177,142 in the first year. The first year contains all procurements, the second year installation and the experimental work.

References

[1] S. Henderson and T. Waite (editors), *Workshop on Energy and Environmental Applications of Accelerators*, June 24-26, 2015, Argonne National Laboratory. http://science.energy.gov/~/media/hep/pdf/accelerator-rd-stewardship/Energy_Environment_Report_Final.pdf

[2] G. Ciovati *et al., Phys. Rev. Accel. Beams* **21**, 091601 (2018).

[3] R. Darlington, E. Barth, and J. McKernan, *Mil. Eng*. **110**(712), pp. 58–60 (2018).

[4] M. R. Cleland and R. A. Galloway, *Physics Procedia* 66, pp. 586 – 594, (2015).

[5] M.J. Berge *et al., Stopping-Power & Range Tables for Electrons, Protons, and Helium Ions*, NIST Standard Reference Database 124, July 2017. https://www.nist.gov/pml/stopping-power-range-tables-electrons-protons-and-helium-ions

[6] A. Ferrari, P. R. Sala, A. Fasso, and J. Ranft, *FLUKA: A multi-particle transport code*, CERN Technical Note CERN-2005-10, 2005.

[7] R. A. Salimov, *High power DC electron accelerators of the ELV type*, AIP Conference Proceedings **592**, 580 (2001).

[8] C. Bott, private communication.

Attachments

A letter of support from Charles Bott, Director of Water Technology and Research, Hampton Roads Sanitation District.

May 29, 2019

Fay Hannon, Ph.D.
Thomas Jefferson National Accelerator Facility (Jefferson Lab)
12000 Jefferson Avenue
Newport News, VA 23606

Subject: **Support for Your Proposal to DOE – "Beamline for e-Beam Processing at UITF"**

Dear Dr. Hannon:

Hampton Roads Sanitation District (HRSD) is pleased to support your proposal to DOE entitled "Beamline for e-beam processing at UITF". Electron beam irradiation has proven to be a viable technology for disinfection, removal of color and odor, and it has to potential to effectively degrade emerging contaminants in water and wastewater. The proposed project aims at developing a beamline at the UITF accelerator to be used for irradiation of samples with an electron beam of energy up to 10 MeV. Given the close proximity between Jefferson Lab and HRSD, the availability of such beamline would allow HRSD to conduct studies on the effectiveness of electron beam irradiation on the degradation of several emerging contaminants in water.

Since its inception in 1940, HRSD has served southeastern Virginia with one mission -- to protect public health and the waters of Hampton Roads by treating wastewater effectively. HRSD provides service to 18 cities and counties of southeast Virginia, an area of over 3,087 square miles with a population of 1.7 million. HRSD operates nine major treatment plants and seven smaller plants in eastern Virginia, with a combined treatment capacity of 249 million gallons per day.

HRSD's newest water treatment innovation is SWIFT, the Sustainable Water Initiative for Tomorrow. SWIFT takes highly treated water that would otherwise be discharged into the Chesapeake Bay watershed and puts it through additional rounds of advanced water treatment to meet drinking water quality standards. SWIFT Water will be used to replenish the Potomac Aquifer, the primary source of groundwater for the region. The $25M SWIFT Research Center (SWIFTRC) in Suffolk, Virginia is now open and replenishing the Potomac Aquifer with one million gallons of SWIFT Water daily. This facility includes a 1.0 MGD demonstration-scale advanced treatment system using an ozone/biofiltration-based configuration, a large research laboratory, a flexible and adaptable space to house the advanced treatment pilot systems and soil columns, a recharge well and network of monitoring wells, an extensometer station to measure land subsidence/rebound, and a SWIFT public outreach and education center. There is a very large sampling and analysis program and a significant research program are being executed as part of the startup and operation of the SWIFTRC. Data gathered from the SWIFT Research Center over the next year will inform design and development of full-scale SWIFT facilities. Once fully implemented in 2030, SWIFT facilities will replenish the Potomac Aquifer with 100

PO Box 5911, Virginia Beach, VA 23471-0911 • 757.355.5017 • Fax 757.363.7189

million gallons of SWIFT Water per day, eliminating more than 90 percent of HRSD's discharge. This could help improve water quality in local rivers and the Chesapeake Bay, while ensuring a sustainable source of groundwater for future generations. Modeling also shows that SWIFT may help slow, reduce or possibly reverse land subsidence caused by withdrawals from the Potomac Aquifer.

There are a number of challenges that could be addressed through the development of a practical and efficient electron beam technology. These include the degradation of problematic emerging contaminants that are difficult or expensive to manager using existing technologies, disinfection of biosolids, and replacement of chemical and energy intensive advanced oxidation processes.

As part of this project, HRSD will be providing an in-kind contribution in the form my time for guidance on the experimental design and preparation and analysis of samples for 1,4-dioxane. We look forward to a successful working relationship with Jefferson Lab on this interesting project. Should you have any questions, please feel free to contact me at 757-460-4228 or cbott@hrsd.com.

Sincerely,

Charles B. Bott, Ph.D., P.E., BCEE
Director of Water Technology and Research
Hampton Roads Sanitation District

Fellow, Water Environment Federation

Adjunct Professor
Charles E. Via, Jr. Department of Civil and Environmental Engineering
Virginia Tech

Adjunct Professor
Department of Civil and Environmental Engineering
Old Dominion University