2022

Beamline for E-beam Processing at UITF

G. Ciovati
gciovati@odu.edu

C. Bott

S. Gregory

F. Hannon

Xi Li
Old Dominion University, xli009@odu.edu

See next page for additional authors

Original Publication Citation

Ciovati, G., Bott, C., Gregory, S., Hannon, F., ... Pearce, R., Poelker, M., & Vennekate, H. (2022). *Beamline for E-beam processing at UITF* (No. 2021-LDRD-LD2111). United States Department of Energy Office of Scientific and Technical Information. https://doi.org/10.2172/1843029.

Authors
G. Ciovati, C. Bott, S. Gregory, F. Hannon, Xi Li, M. McCaughan, R. Pearce, M. Poelker, and H. Vennekate

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Project ID: 2021-LDRD-LD2111

G. Ciovati[1], C. Bott[2], S. Gregory[1], F. Hannon[1], Xi Li[3], M. McCaughan[1], R. Pearce[2,4], M. Poelker[1], H. Vennekate[1]

[1]Jefferson Lab, Newport News, Virginia 23606
[2]Hampton Roads Sanitation District, Virginia Beach, VA 23455
[3]Old Dominion University, Norfolk, VA 23529
[4]Virginia Tech, Blacksburg, VA 24061

Introduction

Electron beam irradiation is a method that has shown a good potential to reduce several pollutants in wastewater [1]. One of the main challenges towards wider adoption of this method is the need for compact, reliable, cost-effective, high-power accelerators. Jefferson Lab is working on the design and prototyping of accelerator components, based on superconducting radio-frequency (SRF) technology, aiming at accelerators for industrial applications [2].

The LDRD project aimed at designing, procuring, installing, and commissioning a beamline at the Upgraded Injector Test Facility (UITF) accelerator to allow electron-beam irradiation studies of different materials, beginning with wastewater. The availability of such beamline allows exploring the ability of electron-beam radiation to reduce or eliminate so-called "forever chemicals" that can be found in wastewater or industrial sites. After successful commissioning, the beamline was used to irradiate wastewater samples with different concentrations of 1,4-dioxane [3], in collaboration with Hampton Roads Sanitation District (HRSD).

Overview of UITF

The UITF is a superconducting radio-frequency (SRF) electron accelerator with a beam energy up to 10 MeV and average current of up to 100 nA in continuous-wave mode. The maximum current is currently limited by the radiation shielding surrounding the accelerator enclosure. The UITF has served multiple purposes such as the development of components for the CEBAF injector, including the commissioning of the new SRF Quarter Cryomodule (QCM) for CEBAF, and the development of a spin-polarized hydrogen-deuterium target (HDIce) for Hall B.

The electrons are produced with a GaAs cathode inside a DC electron gun operated at ~180 kV. The beam is accelerated to ~500 keV and up to 10 MeV by a 2-cell and a 7-cell SRF cavity, respectively, installed in the QCM [4]. Figure 1 shows a schematic layout of the UITF. Before the beginning of this project, beam from the MeV section could be sent to an elevated beamline for the HDIce experiment, to a straight beamline ending into a beam dump or on a spectrometer beamline, also terminated by a beam dump, to measure the beam energy. The irradiation beamline was designed to replace the "straight" beamline.

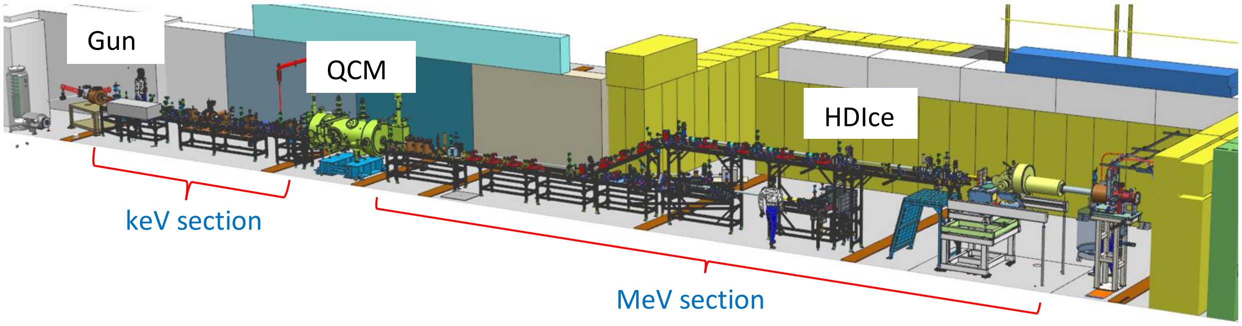


Figure 1: Schematic layout of the UITF at Jefferson Lab.

Beam Transport Simulations

The computer simulation software General Particle Tracer (GPT) [5] was used to study the beam transport from the gun to the irradiation target and guide the design of the new beamline segment. A design beam energy of 8 MeV was chosen, as a compromise between the electrons' penetration depth in water and reliable high-energy operation. The initial particle distribution in the transverse phase space is assumed to be Gaussian with a root-mean-square (rms) width of 0.425 mm in both in both x- and y-direction. The longitudinal space is also assumed to have a Gaussian distribution with a length of $8\times T_{rms}$, where T_{rms} ~ 83 ps is the laser rms pulse length. The electrons are also distributed uniformly in a semi-sphere in the momentum axis coordinate system.

The beam transport simulations aimed at determining the setting of a quadrupole triplet and a defocusing solenoid to achieve a beam radius of the order of ~25 mm at the location of the irradiation target at the end of the beamline. The required beam size was determined by the diameter of the beam exit window. Figure 2 shows a plot of the horizontal trajectories of electrons along the entire UITF beamline, ending at the irradiation target. Figure 3 shows a plot of the energy spread around the 8 MeV mean energy and the beam distribution in the transverse space, both at the end of the beamline. Further details about the beam transport analysis can be found in Ref. [6].

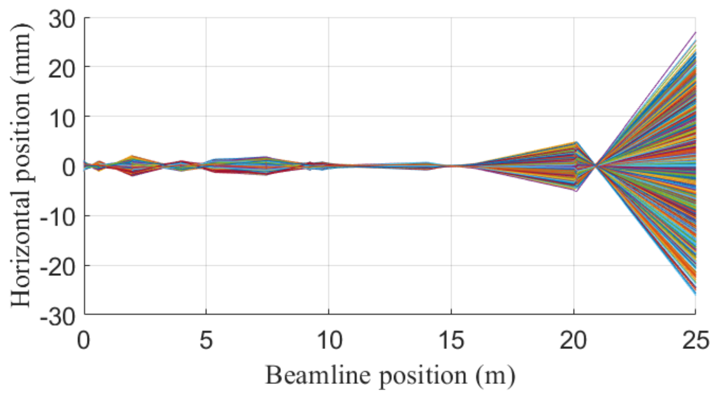


Figure 2: Horizontal trajectories of the electrons along the entire UITF beamline for the selected settings of the quadrupole triplet and defocusing solenoid, located at ~20 m from the gun.

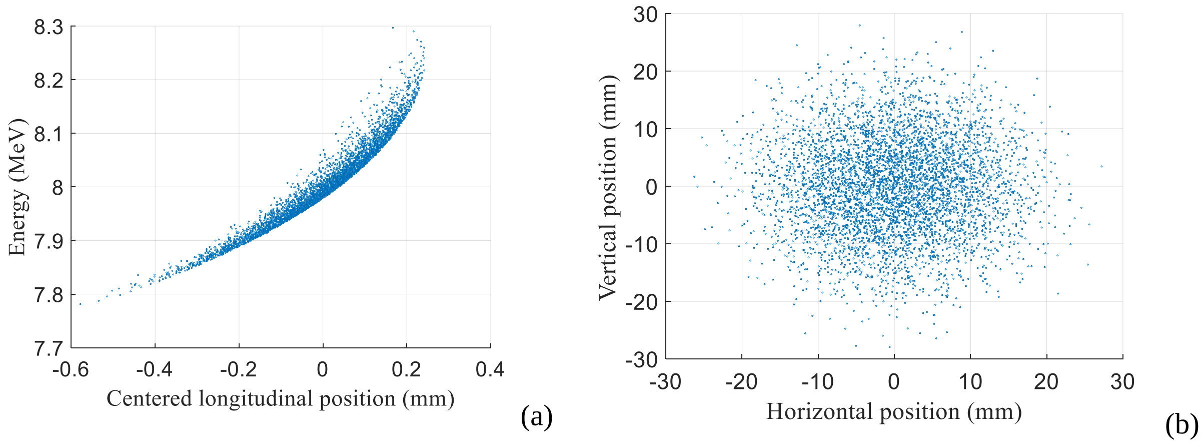


Figure 3: Energy spread (a) and transverse beam distribution at the end of the beamline (b).

Beamline components

Figure 4 shows a schematic layout of the ~5 m long irradiation beamline. The beamline was designed to make use of existing components as much as possible, to reduce cost, and to minimize any risk to the accelerator. The beamline can be isolated from the rest of the MeV section upstream by closing a pneumatic valve. To protect the SRF cryomodule in case of an accident involving sudden venting of the beamline, such as a rupture of the beam exit window, a fast (<10 ms closing time) vacuum valve was procured and installed ~12.4 m upstream of the window, close to the SRF cryomodule. The vacuum gauge controlling the fast valve operation is mounted on the 6-way cross with the Faraday cup at the end of the beamline.

The defocusing solenoid was the one used for the PEPPo experiment [7] and the design operating field for this experiment was 0.22 T (~115 A). The solenoid was fully tested prior to installation in the beamline. The raster coils, beam position monitors, beam viewers and the Faraday cup were recycled from the beamline for the HDIce experiment. The raster coils were installed as an additional option to produce a large, round, uniform beam at the target location.

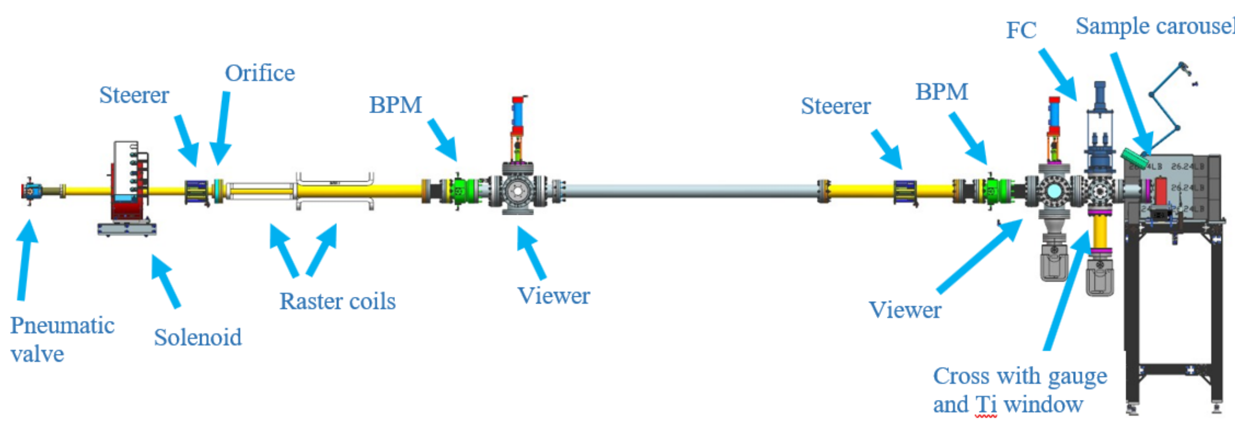
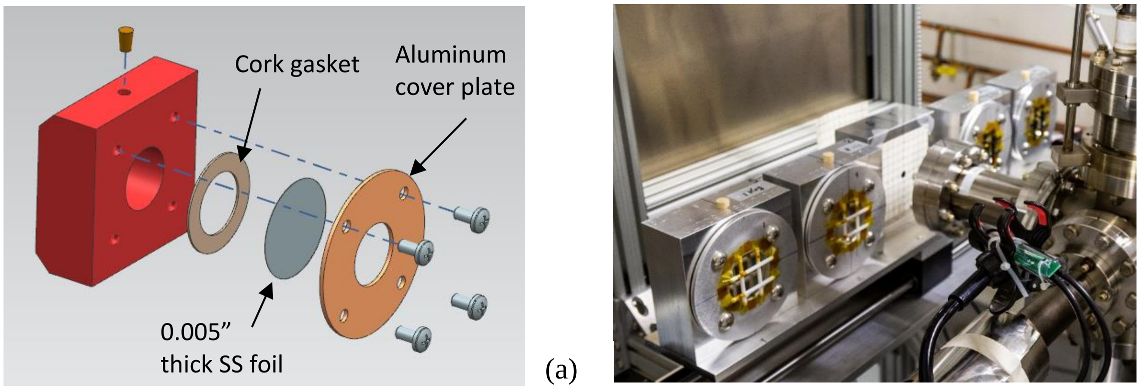


Figure 4: Schematic layout of the irradiation beamline. BPM: beam position monitor, FC: Faraday cup.

The beam exit window is made of titanium grade 2, it is 0.005" thick and it is part of a commercial window-flange assembly [8]. A mechanical and thermal analysis of the window indicates that there should be negligible heating at the design beam parameters and that the beam current could be as high as ~10 μA before the peak temperature of the window would reach ~100 °C [9].

The sample rail consists of a motor-controlled linear translation stage which holds up to five irradiation targets. Each target cell consists of an aluminum block with a ~60 ml (49 mm diameter × 33 mm depth) volume cut-out to be filled with the wastewater sample. The front of the target cell consists of a 0.005" thick stainless steel foil, sealed to the cell with a cork gasket. Figure 5 shows a schematic of the target cell and a picture of the rail with the targets.



(a) (b)

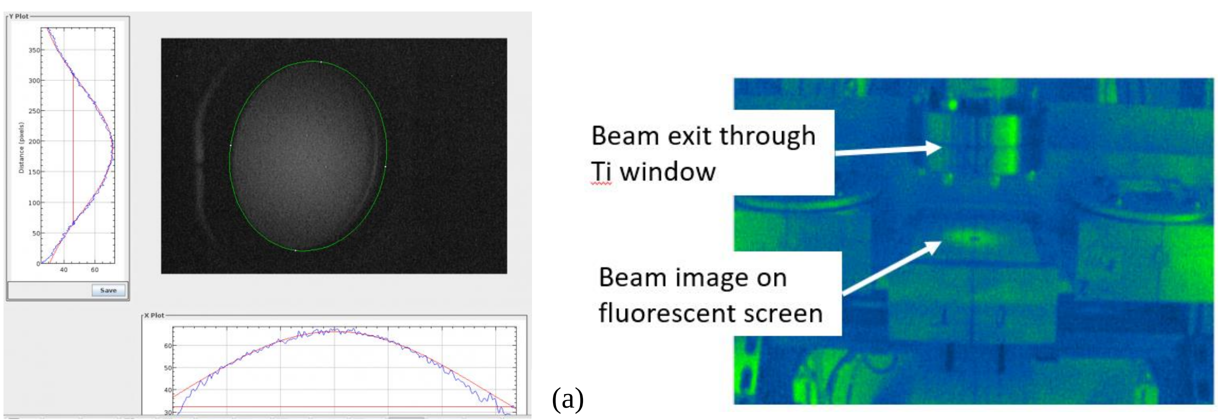
Figure 5: Schematic layout of the irradiation target to be filled with the wastewater samples (a) and picture of 4 targets and one "dummy target" installed on the linear rail.

Beamline commissioning

The functionality of all the installed components was verified during the commissioning of the beamline. Both raster coils and defocusing solenoid were needed to achieve a Gaussian beam distribution with $\sigma_x \sim$ 16 mm and $\sigma_y \sim$ 22 mm at the target location. The settings for the defocusing solenoid and the raster coils were 110 A and 1.9 V with a spiral raster pattern, respectively. The beam size and shape were measured from the image on the beam viewer at ~18" from the targets, as shown for example in Fig. 6.

The beam current was measured using a beam current monitor, which was calibrated with a beam intercepting Faraday cup. A "dummy target" consisting of a solid aluminum block with an X-ray fluorescent screen at the front was placed at the center position on the target rail and it allows measuring the beam shape and size at the target location, as shown for example in Fig. 6.

As part of the commissioning for the experiment, the delivered dose was measured as a function of irradiation time by placing an array of optichromic dosimeters in front of the targets. The measured dose distribution was consistent with the results from simulations obtained with the MonteCarlo software FLUKA [10], for the measured beam energy, current and size.



(a) (b)

Figure 6: Beam image on the 2" beam viewer at ~18" from the target (a) and beam image on X-ray screen on the target rail (b). The dark spot at the center of the screen in (b) was made with a pen marker.

Experimental results

The wastewater samples consisted of 0.5 L bottles with spiked 1,4-dioxane in different matrices. Two 1,4-dioxane concentrations (~8 µg/L and ~80 µg/L) and three matrices were used: de-ionized (DI) water, secondary effluent (SE) wastewater and wastewater filtered with granular activated carbon (GAC). The irradiation time for each combination of 1,4-dioxane concentration and water matrix was in the range 2 – 40 min, corresponding to a dose of ~1 – 20 kGy. The concentration of 1,4-dioxane was measured at HRSD by gas chromatography mass spectroscopy. Preliminary results, shown in Fig. 7, indicate that the concentration of 1,4-dioxane was reduced to below the level of detection by a relatively low dose of electron-beam radiation.

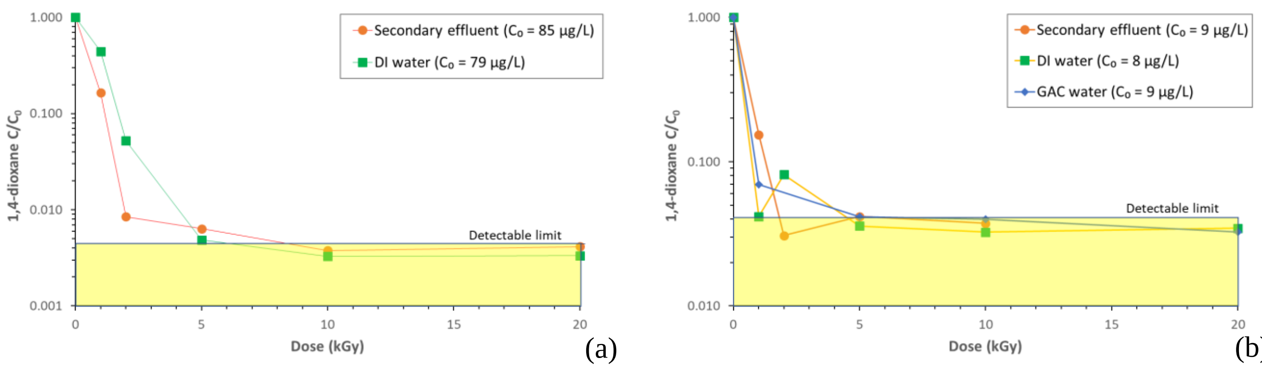


Figure 7: Preliminary results on the decrease in the concentration of 1,4-dioxane, starting at ~80 µg/L (a) and ~8 µg/L (b), in different water matrices, as a function of electron-beam radiation dose.

Summary

We have successfully designed, installed and commissioned a new beamline at UITF that allows electron-beam irradiation of a target. A beam size of the order of ~55 mm in both transverse directions was achieved by means of two pairs of raster coils and a defocusing solenoid. A motorized linear translation stage allows irradiation of multiple targets, without entry in the accelerator vault.

Irradiation experiments were carried out in collaboration with HRSD on wastewater samples with spiked concentration of 1,4-dioxane. Preliminary results are very promising in terms of the ability to significantly reduce the contaminant with a relatively low dose.

In the near future, we plan on continuing the collaboration with HRSD to study the effect of electron-beam irradiation on perfluoroalkyl and polyfluoroalkyl substances, which represent an emerging and growing challenge to the wastewater industry [11, 12]. Different type of wastewater samples, such as from fracking operations or farm effluents could also be treated by electron-beam radiation using the beamline developed with this project. Improved shielding of the UITF vault in the near future would also allow increasing the beam current to 1 µA, enabling faster delivery of higher radiation doses.

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