NUMERICAL STUDY OF 5 MeV SRF ELECTRON LINAC FOR WASTEWATER PURIFICATION*

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Abstract

Superconducting Radio Frequency (SRF) technology is a proven solution for generating high-power electron beams (EB), suitable for tasks like purifying wastewater from challenging impurities such as PFAS. This study elaborates on effectiveness of EB treatment and outlines design considerations for a 1.3 GHz SRF linac operating at 5 MeV with an average beam current of 10 mA. Numerical analyses for the accelerator system, ensuring that the beam reaches 5 MeV with the desired characteristics, lead to a compact beamline structure. This structure includes a 100 kV thermionic gridded gun, a 1.3 GHz 3-cell low beta buncher cavity, and three 2-cell 1.3 GHz accelerator cavities, along with necessary focusing solenoids, all fitting within ~3 meter. Given the need for high beam current, achieving a high bunch repetition rate is important. We therefore will employ the RF gating to the grid of the electron gun. The results of the numerical studies will be presented at this conference.

INTRODUCTION

The growth of industrialization has led to the introduction of various persistent organic pollutants (POPs) in wastewater, including pharmaceutical and personal care products (PPCPs), endocrine-disrupting chemicals (EDCs), and per- and polyfluoroalkyl substances (PFAS). These pollutants are resistant to the available treatment methods, necessitating the development of more effective solutions. PFAS, known for their high stability and resistance to degradation, are particularly challenging. Conventional methods available has been observed to be insufficient to destruct such stubborn impurities. On the other hand, Electron beam (EB) technology has been observed to be offering a promising approach to decompose these substances by initiating chemical reactions that break down these contaminants [1]. However, PFAS needs high dosage to be decomposed, which can be provided by high power EB accelerator. In this paper, we therefore have discussed our design of a high power SRF electron linac for wastewater purification.

DESIGN & PARAMETERS

To design the accelerator for environmental applications, we need to set parameters such as beam energy and beam current. Specifically, the beam energy must be below 10 MeV to avoid inducing radioactivity in water. On the other hand, lower energy levels allow for a smaller and more cost-effective accelerator. However, the penetration depth of electrons in water decreases with lower energy [2] as shown in the Fig. 1, complicating the construction of an effective irradiation system. Therefore, we chose a beam energy of 5 MeV, striking a balance between being neither too high nor too low.

For beam current, there is no upper limit, but the achievable beam current is constrained by the available power coupler. As an initial target, we aim for a beam current of 10 mA, resulting in a 50 kW system. SRF offers the advantage of CW operation allowing to achieve high average current. The final design as depicted in Fig. 2 has considered SRF accelerator. The design has developed through simulations using KUCODE [3] with gaussian bunch of 70 ps RMS (FW ~ 400 ps) and 8 pC bunch charge at the cathode. This is a 3 m long system that includes a DC, HV, thermionic gridded electron gun, a Multicell or 3-cell buncher and three 2-cell main accelerating cavities. The whole system is operating at single fundamental frequency of 1.3 GHz, simplifying the requirement of RF system significantly. The buncher and accelerator cavities will be

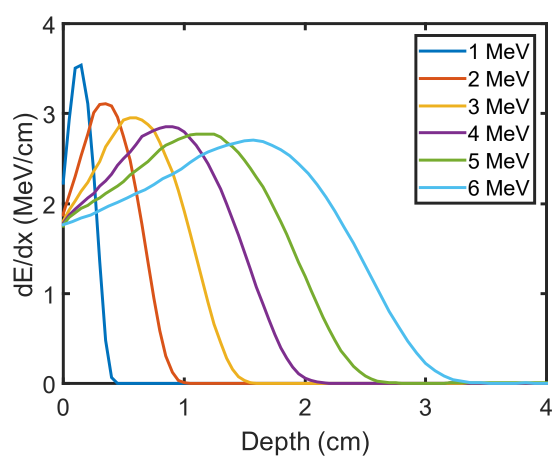

Figure 1: Penetration depth of electron incident on water with different energies.

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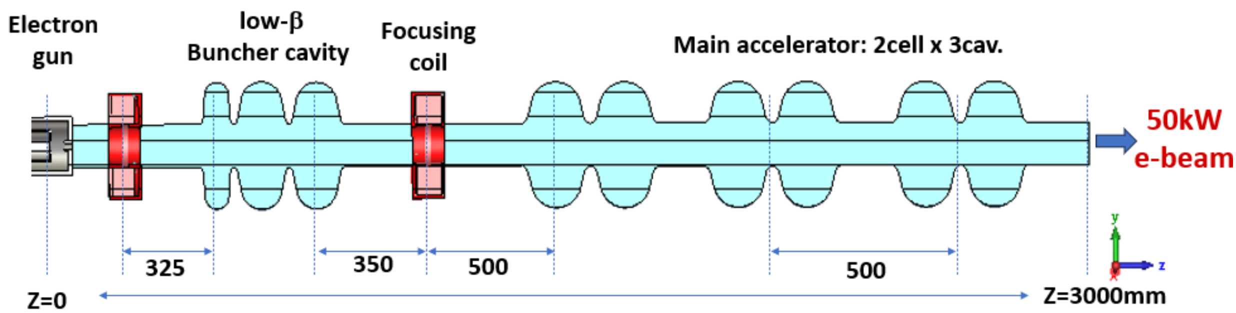

Figure 2: Configuration of designed superconducting RF electron linac.

made up of Nb3Sn to be able to use conduction cooling making the system liquid helium free and hence compact. Acceleration gradient is considered of 10 MV/m in all the cavities, which has already been achieved in experimental tests by conduction cooling [4].

ACCELERATOR SYSTEM

Electron Gun

Electron gun in the design is a thermionic gridded with a cathode (Y646B, 8 mm diameter) operating at 100 kV DC high voltage. The requirements from the electron gun include generating short electron pulses and continuous wave (CW) operation for achieving the high average current. To achieve this, RF gating [5, 6] of the grid will be employed with which we are hopeful to generate the electron pulses of length < 400 ps (FW).

3-Cell Low Beta Cavity

The design of a 3-cell buncher cavity aimed to achieve bunching and energy boosting of electrons with no beam loss, reaching a beta close to 1. The first cell of the cavity was designed with a beta of 0.5, corresponding to the 100 kV high voltage of the electron gun. The second and third cells were designed with a beta of 0.8, as initial simulations indicated the particle beta was approximately 0.8. In this configuration, the first cell functions as a buncher, while the second and third cells serve as boosters. The compactness of this cavity design eliminates the need for a drift space for bunching, which would be required if separate buncher and booster units were used. While separate units would allow for independent phase optimization, simulations revealed that such a configuration would cause energy spread due to leakage fields for bunch lengths longer than the acceptable range of 1.3 GHz. By combining the cells, we addressed this issue, resulting in an efficient and compact solution.

2-Cell Accelerator Cavity

This is a standard 1.3 GHz accelerating cavity which has operated at 10 MV/m in the simulations. Three such cavities have been considered to be able to reach aimed 5 MeV beam energy. The phase of the first cavity was chosen to minimize energy spread, and the phases of the remaining cavities were selected to maximize energy gain.

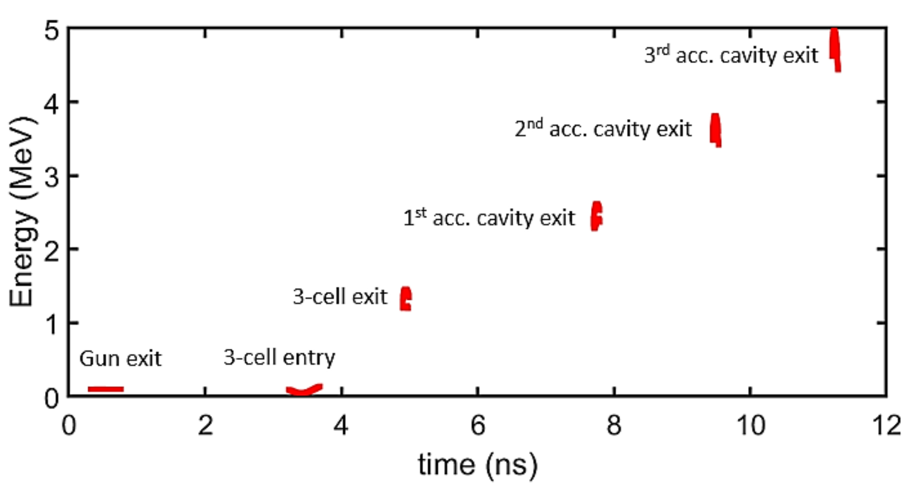

Figure 3: Evolution of longitudinal phase space distribution of electron beam along the linac.

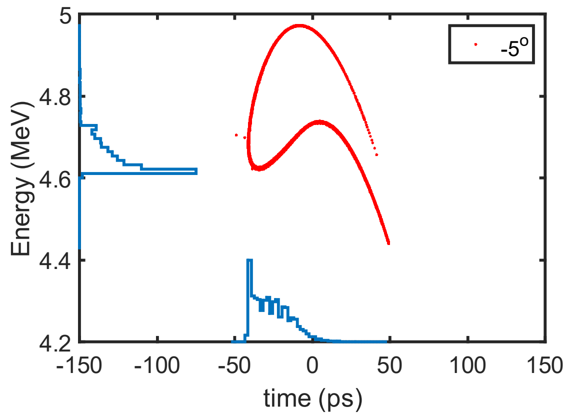

Figure 4: Longitudinal phase space distribution of the final beam output at exit of 3rd accelerating cavity.

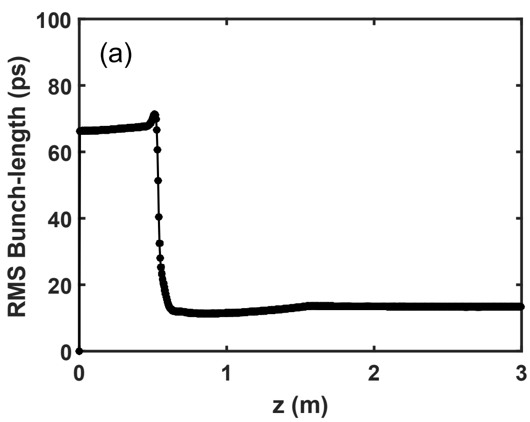

Figure 5: RMS Bunch-length variation along longitudinal direction.

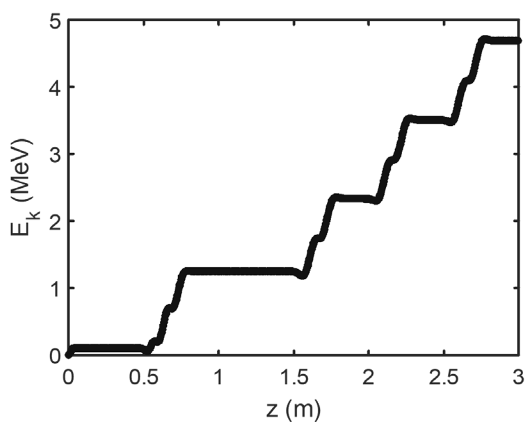

Figure 6: Kinematic energy gain of electrons along longitudinal direction.

RESULT

The beam output obtained at every stage is as shown in Fig. 3. Figure 4 shows the longitudinal phase space distribution of the final beam output downstream the 3rd accelerating cavity. Figure 5 shows a bunch with a length unchanged from the buncher, Fig. 6 shows an energy gain of approximately 4.7 MeV, and Fig. 7 shows an energy spread of 0.6% at the distance of 3 m from cathode surface. Although we could have opted for a longer bunch length at the buncher, however, we wanted to keep the final bunch as compact as possible so that this whole structure could be used as an injector for high energy stages.

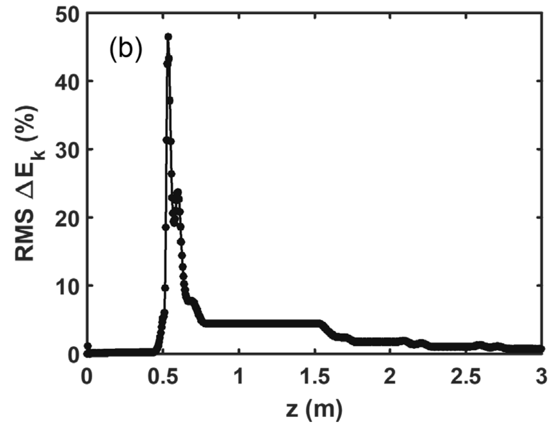

Figure 7: Variation of RMS Kinematic energy spread of electrons along longitudinal direction.

SUMMARY & FUTURE PROSPECTS

This study demonstrates the design and numerical analysis of a compact SRF electron linac aimed to use for effective degradation of PFAS in wastewater using electron beam radiation. The system includes a DC 100 kV high-voltage thermionic gridded electron gun with RF gating, 1.3 GHz buncher, and accelerator cavities, achieving a beam of 5 MeV at 10 mA average current. The use of Nb_3Sn for the SRF cavities, with conduction cooling, eliminates the need for liquid helium, contributing to the compact design. Final simulations indicated a bunch length of 32 ps (FWHM), a mean energy of 4.68 MeV, and an energy spread of 0.7%. Simulations highlighted the requirement for an electron gun that can generate pulses ~ 400 ps (FW). Future prospects include testing RF gating for an available source of 1.5 GHz, 100 W, with an expected pulse width of approximately 260 ps, and subsequent measurements of bunch length and emittance.

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