A STUDY OF EMITTANCE GROWTH IN A PHOTOINJECTER LINAC BY USING PWT AS PRE-ACCELERATOR

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Abstract

The NSRRC high brightness photo-injector for light source R&D is a 2998 MHz split configuration. Our goal is to produce 1 nC bunch charge from a photo-cathode RF gun with normalized emittance of 1 mm-mrad or less. However, limited by the available power from our klystron, previous studies showed that our linac has to be equipped with focusing solenoid to help emittance control during acceleration. In order to omit the bulky focusing solenoid from the booster linac system, we considered to use two high gradient (~26 MV/m) PWT standing-wave structures to accelerate the beam previous to the linac. Studies showed that this configuration can keep the emittance as low as 1 mm-mrad while also decreasing the energy spread to half of its initial amount. The only drawback is the growth of final beam radius, which can be compensated by using a setting of quadrupole magnets.

INTRODUCTION

Ultra-short and low emittance electron beams have been studied intensively to be used in many research fields such as free electron laser, ultra-fast electron diffraction and generating short pulse X-ray. An R&D program has been carried to build up the expertise on high brightness electron beam and advanced linear accelerator technologies.

A 150 MeV pre-injector linac system will be installed for the ongoing 3 GeV Taiwan photon source (TPS) project [1]. This pre-injector system will be tested in a 40 meters tunnel. It has been suggested to use this tunnel for FEL and advanced accelerator research after this linac system has been moved to its final location in the TPS facility building. Therefore, as a stage of this high brightness electron beam R&D program, we are proposing to build a few hundred MeV high brightness driver linac (a test facility) in this tunnel for short wavelength high gain FEL experiments.

At the first step of this driver linac, a split photo-injector with solenoid magnet to help focusing and emittance control of electron beam in the booster linac will be used [2]. The photo-cathode RF gun produces a 10 ps long bunch with the charge of 1 nC. The booster linac of this photo-injector system is a 5.2 m long, constant gradient travelling-wave structure operating at 2π/3 mode. This linac structure is similar to the DESY LINAC-II design and is manufactured by Research Instruments GmbH (RI). The available microwave power from the existing Thales 2100A klystrons are limited to 35 MW. Therefore, the nominal gradient field of the first linac section can only be set at 18 MV/m. At this gradient, bulky focusing solenoid magnetic field will be needed to keep emittance under control during early stage of beam acceleration in the booster linac. Evolution of beam emittance and RMS beam size along the photo-injector with focusing solenoid around the booster linac are shown in Fig. 1. The beam parameters at the exit of NSRRC split photo-injector with focusing solenoid around the booster linac are shown in Table 1.

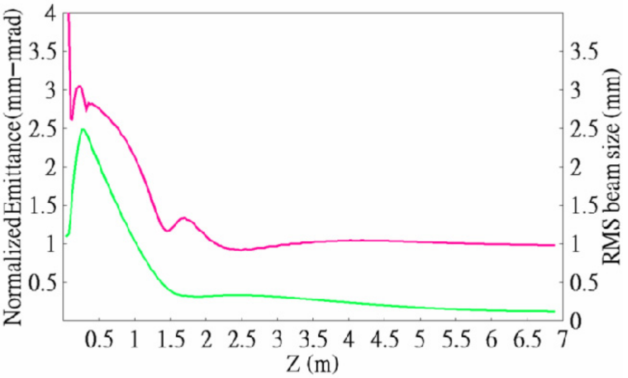

Figure 1: Evolution of normalized beam emittance and beam size along the photo-injector with solenoid around the booster linac.

Table 1: Beam parameters at the exit of NSRRC split photo-injector with focusing solenoid around the booster linac.

Final normalized emittance	0.962 mm-mrad
Final energy spread	0.28%
Final beam energy	76.4 MeV
Final rms beam radius	0.14 mm

MODEL FOR EMITTANCE GROWTH COMPENSATION

Developed by L. Serafini and J. B. Rosenzweig [1,3], this model provides an analytical description for the transverse dynamics of intense, relativistic and space-charge dominated beams undergoing strong acceleration in RF photo-injectors. It is based on a particular solution of the envelope equation for an accelerated beam, which is invariant under reversible emittance transformations, termed invariant envelope. This concept and the method of analysis are of interest and applicable to any relativistic beam that is space charge dominated and accelerated in high gradient linear accelerators.

In this case the beam undergoes cold plasma oscillations, in which the space charge force is mostly dominant over the emittance growth. The frequency of the plasma oscillations, due to mismatches between the space charge force and the external focusing gradient, is to first order independent of the current while the betatron motion is almost absent. In fact it is the frequency independence that leads to reversible normalized emittance oscillations. Accelerating the beam on the invariant envelope damps these oscillations, so that the normalized emittance at the injector exit reduces to a steady state minimum when the oscillations are properly tuned. The RMS projected normalized emittance $\varepsilon_n = \langle\beta\gamma\rangle\sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}$ oscillates with a frequency $\sqrt{2K_r}$ at an amplitude $\Delta\varepsilon_n \propto \sqrt{\hat{I}/\gamma}$ whenever a bunched beam is matched into a focusing channel of gradient K_r,

$$K_r = \left[\frac{\eta}{8} + b^2\right]\left(\frac{\gamma'}{\gamma\sin(\phi)}\right)^2 \qquad (1)$$

where $b=cB_z/E_0$, B_z is the solenoidal magnetic strength, E_0 is the accelerating electric field on the beam axis, ϕ is the particle phase with respect to the RF field wave which should be kept equal to π/2 for emittance minimization, and the quantity η is a measure of the higher spatial harmonic amplitudes of the RF wave. It is usually close to 1 for conventional standing wave linacs and close to 2 for 2π/3 travelling wave linacs while it is almost negligible for π/2 travelling wave ones. In the case of PWT linacs, η is equal to 3 [3,4].

Given the assumption of space charge dominated envelope motion, it is possible to ignore the term which represents the contributions to envelope forcing due to the emittance arising from both random, thermal sources as well as the effects of nonlinear macroscopic forces. It is also possible to ignore the first and second derivatives of the beam envelope variations due to the paraxial approximation. Therefore, the emittance at the equilibrium flow condition for a slice at a given value of slice position $\zeta=z-\beta ct+z_0$ would be

$$\sigma_{eq}(\zeta) = \sqrt{\frac{I(\zeta)}{2I_0(\beta\gamma)^3 K_r}} \qquad (2)$$

where σ is the beam envelope size, eventually slice dependent, $\hat{I}$ is the peak current and $I_0 = 17\,kA$ is the Alfven current.

By writing the expression above for γ' we have

$$\gamma' = \frac{\sin(\phi)}{\sigma_{eq}(\zeta)}\sqrt{\frac{I(\zeta)}{2I_0\beta^3\gamma\left[\frac{\eta}{8}+b^2\right]}} \qquad (3)$$

where $\gamma' = eE_{acc}/mc^2 \approx 2E_{acc}$, E_{acc} is the accelerating field. When the beam has enough energy, space charge forces will no longer affect the beam envelope so no further external focusing forces are required. The laminar regime extends up to an energy given by [4]:

$$\gamma = \sqrt{\frac{8}{\eta}}\frac{I}{2I_0\gamma'\varepsilon_{n,th}} \qquad (4)$$

In our case, the rms radius at the beam waist is 0.33 mm, gamma is 13.4, and peak current is 100 A. Therefore, the required accelerating gradient to achieve invariant envelope and keep the emittance constant without solenoid around the booster linac is ~45 MV/m.

PWT AS PRE-ACCELERATORS

The 45 MV/m accelerating gradient for the booster linac is impossible to achieve not only because of the klystron output power limitation, but also for the probability of RF breakdown inside the linac. Therefore, a new setup was proposed consisting of 2 PWT pre-accelerating tubes before the final acceleration in the long linac. Since PWT tubes has the advantages of higher accelerating gradient and also more focusing forces during acceleration, it can keep the emittance constant until the beam reaches the enough energy so that the accelerating gradient of the long linac would be sufficient for further acceleration under the invariant envelope condition.

PWT is a standing wave linac, excited in π mode. It consists of a cylindrical cavity, loaded with disks. The disks are separated from the cylindrical tank and supported by four steel rods parallel to the axis. The RF is coupled via the large concentric cylindrical cavity. Because of the higher amount of RF energy inside the structure and also strong coupling between individual cells, PWT linac has higher shunt impedance, quality factor and accelerating gradient than other conventional linacs [5].

The PWT's design for NSRRC photo-injector consists of 7 cells with two end-cells. Figure 2 shows the E-field distribution inside the designed PWT tube calculated by SUPERFISH.

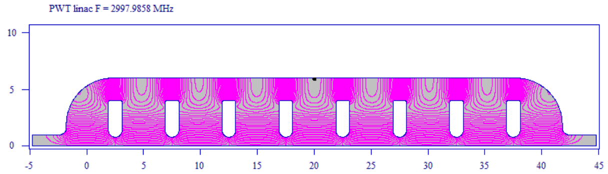

Figure 2: E-field distribution inside the PWT structure; calculated by SUPERFISH.

As mentioned before, for a standing wave PWT structure, η is 3. As a result, the required accelerating gradient to have invariant envelope will decrease to ~ 37 MV/m. Although it is less than the required gradient in the long linac, it is still large and hard to achieve in a PWT tube. Therefore, a new approach was chosen. According to Eq. 3, if the beam radius at the waist is increased, less accelerating gradient would be required to keep the emittance constant. This was done by decreasing the solenoid magnetic strength from 0.258 T to 0.254 T. In this case, the beam radius at the waist will increase to 0.52 mm and the required accelerating gradient will decrease to ~ 30 MV/m and ~ 26 MV/m for the booster linac without solenoid and PWT tube, respectively.

After the acceleration through two PWT tubes with accelerating gradient at 26 MV/m, the beam energy will reach ~ 32 MeV. At this point, the required accelerating gradient in the long linac to keep the emittance constant will be only 18 MV/m.

Final optimizations were done using the code PARMELA to calculate the best injection phase of electron bunches into the PWT tubes and long linac to achieve the minimum energy dispersion as well as the lowest possible beam emittance. Evolution of beam emittance and RMS beam size along the photo-injector with focusing solenoid around the booster linac are shown in Fig. 3 and the electron distributions in transverse and longitudinal phase spaces are shown in Fig. 4. The beam parameters at the exit of NSRRC split photo-injector with focusing solenoid around the booster linac are shown in Table 2.

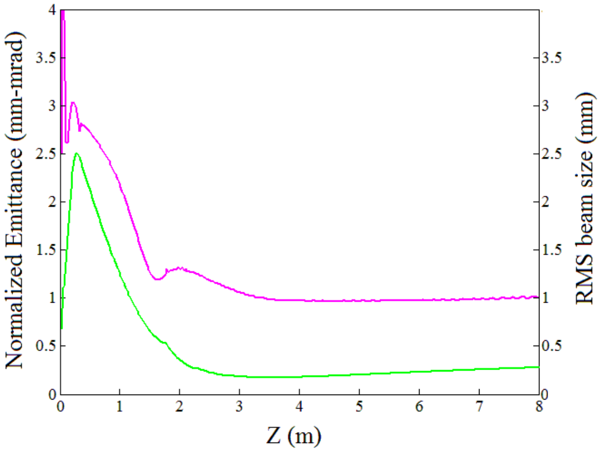

Figure 3: Evolution of normalized beam emittance and beam size along the photo-injector with PWT pre-accelerators.

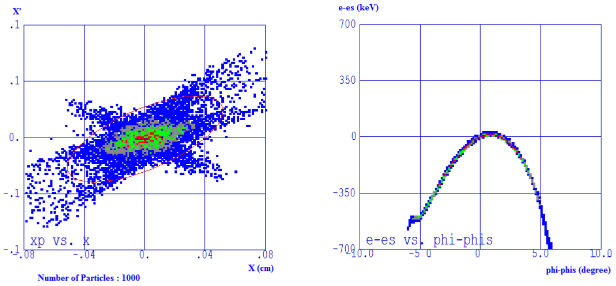

Figure 4: Electron distributions in transverse (left) and longitudinal (right) phase spaces.

Table 2: Beam parameters at the exit of NSRRC split photo-injector with PWT pre-accelerators.

Final normalized emittance	1.005 mm-mrad
Final energy spread	0.14%
Final beam energy	121.5 MeV
Final rms beam radius	0.31 mm

CONCLUSION

Our work has successfully demonstrated the feasibility of using high gradient PWT pre-accelerators for emittance control in photo-injectors. These standing wave linacs can substitute the heavy and bulky solenoid required around the booster linac in order to control the emittance growth during acceleration. This approach can also lead to less energy spread in the output beam. The only problem is more final beam radius which can be easily compensated with a lattice of quadrupole magnets. Future studies on the emittance control with PWT linacs include developing the PWT prototype and cold testing the structure, and inclusion of the effects of wake field in the simulation.

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