AN INTEGRATED TRAVELING-WAVE PHOTOINJECTOR

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Abstract

Integrated photoinjectors have the potential to provide compact, low cost, high brightness electron beams, and are attractive for scaling to frequencies beyond S-band. Traditionally, they have been built as standing-wave devices. We are developing a novel high-brightness electron source that couples a two-cell standing wave cavity directly to a multi-cell traveling-wave structure. This configuration offers a number of advantages over the split standing-wave systems, most notably the almost complete removal of the reflected RF transient, and the absence of the bunch lengthening that occurs in the drift section of split systems. We will discuss these and other advantages, as well as provide results of our beam dynamics study.

BACKGROUND

The last fifteen years has seen a revolution in the production of high brightness electron beams due to the evolution of the RF photoinjector. This evolution derives its genesis from a multi-disciplinary approach to the difficult problems presented to the understanding of the behavior of a electron beam under the combined influence of large external applied electromagnetic fields and the self-induced space charge fields. Through these theoretical, computational, and experimental investigations, photoinjector physics has established itself at the confluence of a large number of disciplines, including accelerator beam dynamics, plasma physics, large-scale computational physics, surface studies, high-field RF physics and laser engineering. The manifest success of the RF photoinjector is a testament to this collective understanding.

The most prevalent photoinjector design in use today employs an arrangement of two accelerating structures split between a BNL/UCLA/SLAC-style 1.5/1.6 cell SW gun [1] and a post accelerating linac, separated by a ≈ 10 RF wavelength drift section. In these highly-optimized designs, the operating gradient in the gun is in excess of 100 MV/m. While extremely successful in providing ultra-high brightness beams for diverse applications, the split systems offer a number of obstacles in the path of the further evolution of the photoinjector. First, because of the photoinjector scaling laws, there is significant interest in the photoinjector community toward scaling existing designs to frequencies beyond S-band. However, because of the magnitude of the fields in the split system, scaling above s-band is greatly limited by RF breakdown. Second, all split systems exhibit bunch lengthening due to the presence of the drift section, which itself is essential for proper emittance compensation.

An alternative design, less popular yet perhaps even more successful, is exemplified by the LANL integrated L-band injector or the UCLA/DULY PWT Photoinjector [2], which integrates the gun and the linac and operates at lower overall gradient. While these systems do not exhibit pulse lengthening, the scaling of the designs, which initially seems promising is limited by the inherent difficulties in designing long SW structures, particularly at high frequencies. As a result, while these systems are compact, they are unable to provide beams with energies above 18 MeV.

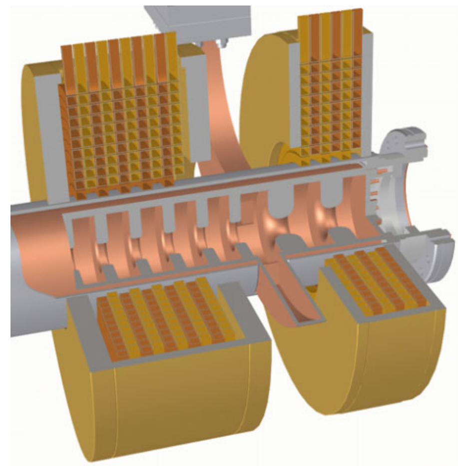

Figure 1: The first few cells of the hybrid photoinjector showing the emittance-compensating solenoid system.

In order to circumvent these and other limitations existing photoinjector designs we have studied a device which we call the “hybrid” photoinjector, whereby a relatively high-gradient two-cell standing wave structure is on-axis coupled directly to a long (≈ 2 m) $2\pi/3$ constant-impedance traveling wave accelerating section. The structure is coupled to the feed guide through the initial TW coupling cell. The first few cells of the hybrid photoinjector are shown in Figure 1. This design offers a number of advantages over both split and integrated existing designs, namely:

- Higher energies and better efficiency in power usage since most of the acceleration takes place in the TW section.
- Overall low gradients make it easier to hold RF voltages in cavities and improve vacuum.
- Robust accelerator dynamics, allowing flexibility in operating energy by simply changing RF power and laser injection parameters.
- Flexible emittance compensation beam optics because of the introduction of a dual-coil solenoid.
- Near complete removal of the transient RF reflected

power since the structure is coupled to through the low Q TW cell. This feature is extremely important for scaling beyond s-band, where high-power isolators are expensive or non-existent.

- Simplifies the high power RF feed system required by split systems.
- Avoids the bunch lengthening observed after the exit of the 1.6 cell gun during the drift in a split system. The slow decrease in gradient enhances the emittance compensation process.
- Easier to fabricate, tune and operate than an integrated SW system of equivalent energy.

DESIGN OF THE DEVICE

The critical RF issue for the hybrid photoinjector is the design of the input coupling cell. The input cell connects both TW and SW sections to the feed guide, and so must provide an impedance match to two different structure impedances. To facilitate the coupler design process, we derived a circuit model which was solved numerically using a C program. The circuit model allows us derive a match condition by varying the Q, cell resonant frequency, and cell-to-cell coupling strength. To derive a match for the input cell, we first constructed a matched TW structure with no coupling to the SW section, and then slowly increased coupling while adjusting the input cell parameters to maintain a matched condition. In this way we were able to rapidly arrive at a set of matched coupler parameters.

The circuit model was also used to investigate the transient behavior of the device. Because the input coupling cell has a relatively low Q value ($\approx$ 600), the large initial reflected transient seen in SW structures such as the 1.6 cell gun, is suppressed in the hybrid structure. Circuit model results verified this characteristic. As a further check on these results, we used the time-domain finite-difference electromagnetic solver GdfidL [3]. Results from GdfidL qualitatively agreed with our circuit model.

For the design of the TW section we have chosen a long, $\approx$ 2 m, TW structure run at a nominal average gradient of $eE_{ave} = 13.5$ MV/m. For an optimized constant-impedance structure, this implies a power usage of roughly 17 MW. With an additional 3 MW for powering the 1.6 cell SW gun component of the structure, the total power needed is 23 MW, which is well within the reach of commercial S-band klystrons (¡30 MW standard). The 3 MW 1.6 cell power budget is chosen to yield a peak acceleration gradient on the cathode of $E_0 = 70$ MV/m ($\alpha = 1.1$), which places notably higher in gradient than a SW integrated injector. This is again allowed by the separation of gradient levels allowed in the hybrid structure, as this higher gradient is confined to a very small part of the structure. Initial explorations of the beam dynamics with even higher gradients in the 1.6 cell part of the hybrid have yielded promising results, as is discussed below. The issue of allowable difference between the acceleration gradients in the 1.6 cell SW portion and the TW portion of the structure is of course a subject which ties the RF design to the beam dynamics.

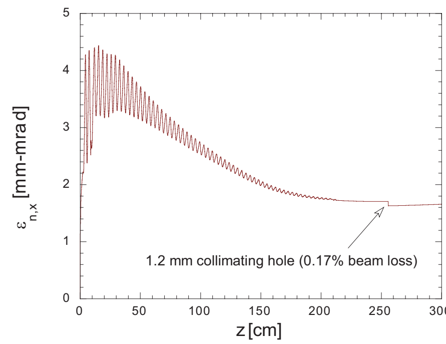

Figure 2: PARMELA results for the evolution of the transverse normalized rms emittance in hybrid injector. Effects of collimation (1.2 mm radius tube) of beam edge shown.

BEAM DYNAMICS

Studies of the beam dynamics in the injector were performed with UCLA PARMELA, multi-particle space-charge tracking code, as well as HOMDYN, a code which solves for the dynamics of the beam envelopes of the bunch associated with a large number of beam "slices". This slice-envelope model is indeed quite accurate in identifying the basic characteristics of a photoinjector working point, and is much faster than PARMELA. Once the working point is established with HOMDYN, one may proceed confidently to more detailed investigations with PARMELA. The field maps used in these dynamics simulations were obtained from magnetostatic POISSON and electromagnetic SUPERFISH modeling.

The higher gradient SW acceleration produces an energy of around 3.5 MeV, while the long TW section then brings the beam up to around 30.6 MeV ($\gamma = 60$). There is flexibility in choice of the final accelerating phase in the TW section, by adjusting the initial launch phase. This is akin to the case of the integrated injector, but unlike the split injector, where a large penalty is paid in induced "RF emittance" when one exits the gun at the incorrect phase. The choice of phasing allows tuning of the final longitudinal phase space for a given application, and enables operation at different RF field levels. The longitudinal beam evolution is noteworthy in that there is negligible bunch lengthening after the SW part of the structure. This allows the final bunch length to be 10% *shorter* than a standard 1 nC case with the split photoinjector. As peak current is even more important than emittance is many applications (*e.g.* wakefield acceleration driver, Thomson scattering), this is a significant advantage over existing devices.

The rms normalized emittance evolution for the nominal working point is displayed in Figure 2. The emittance compensates to a full value of 1.75 mm–mrad. This value is dominated by the tails, however, as collimation of only 0.17% of the beam charge lowers the emittance by a no-

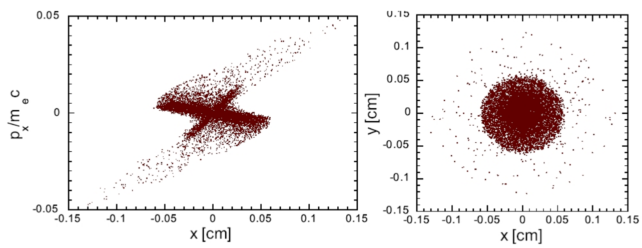

Figure 3: Final horizontal phase space, and transverse configuration space emitted from hybrid injector given by PARMELA

ticeable amount. Inspection of the transverse (horizontal) phase space, and configuration space shown in Figure 3 illustrates the reason for this sensitivity, as a fairly extensive halo which contains a very small amount of the beam charge surrounds the dense core of the beam. This halo exists mainly in the leading and trailing edge of the beam, where the beam slices do not come to a space-charge dominated waist. These components of the beam are typically ignored in applications, and in fact may be effectively collimated.

CONCLUSION

We have designed a hybrid SW to TW integrated photoinjector that shows significant promise for a compact, efficient 30 MeV source of high-brightness electrons. In further stages of this work we plan to further explore RF optimizations, particularly shaping of the peak field profiles in the TW section in order to optimize the results of our initial beam dynamics study. We also plan to perform a rigorous thermal and mechanical analysis before finally fabricating a prototype, which will be commissioned at the UCLA PEGASUS Laboratory.

REFERENCES

[1] D. T. Palmer, PhD Thesis, Stanford University, 1999.

[2] X. Ding, PhD Thesis, UCLA, 2000.

[3] W. Bruns, Proceedings of the 1997 Particle Accelerator Conference, 2018, 1997.