INITIAL BEAM RESULTS FROM THE CORNELL HIGH-CURRENT ERL INJECTOR PROTOTYPE

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Abstract

Cornell University has built a high average current electron injector for use with an Energy Recovery Linac. The injector is designed for up to 100 mA average current at 5 MeV (33 mA at 15 MeV) and is expected to produce the ultra-low emittances needed for an ERL. An overview of the initial performance of this injector, the status of beam commissioning, and a summary of experiments being undertaken to demonstrate low emittance and high average current are presented.

INTRODUCTION

An Energy Recovery Linac light source is being planned at Cornell University [1]. This approach promises diffraction-limited quasi-continuous synchrotron radiation in the hard X-ray spectral range and picosecond or shorter pulses for the X-ray scientific user community. A number of challenges must be overcome before construction of the ERL, including demonstration of a suitable source capable of delivering a 100 mA average current low emittance beam as well as the prerequisite high-efficiency CW supercoducting RF structures. The realization of these challenges led us to propose an ERL prototype (also known as Phase1a) in 2001 seeking to address these questions.

Table 1: Cornell ERL Prototype Requirements

Beam energy	5-15 MeV
Max average current	100 mA
Max beam power	0.5 MW
Bunch length	2-3 ps rms
RMS normalized transverse emittance	≤2 µm at 77 pC/bunch
Operating Frequency	1.3 GHz (CW)

The set of main parameters incorporated into the ERL prototype injector is shown in Table 1. The initial goal is to demonstrate 2 µm rms normalized transverse emittance at 77 pC per bunch, and to develop a roadmap towards achieving much reduced values.

PROJECT OVERVIEW

In addition to demonstrating a practical electron source suitable to drive the ERL light source, the project seeks to establish mastery and expand one's understanding in a number of accelerator-related technology and physics areas: to identify the physics limits to the maximum beam brightness achievable from high current photoinjectors operating in the space-charge dominated regime; gun and laser technology; photocathodes; superconducting RF frontiers including efficient damping and removal of the unwanted higher order mode beam induced power from the cryogenic environment, low-level RF field controls, etc., see [2].

The project received funding from the NSF in 2005, which led to the construction of the injector prototype currently in commissioning. Here we summarize beam experiments undertaken as a part of this project so far and present our short-term future plans towards achieving the goal of realizing the photoinjector suitable for the ERL light source.

Beam experiments addressing outstanding questions for low-emittance high-current beam production have been carried in two different accelerator beamlines: at low energy in the DC gun beamline operational between late 2006 and spring 2008, and in the 5-15 MeV photoinjector, which is under commissioning since summer 2008.

DC Gun Beamline

Figure 1 shows the DC gun beamline used in several studies such as photocathode characterization, laser shaping, and space charge measurements from the gun.

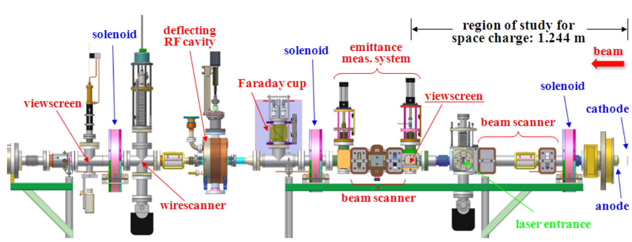

Figure 1: DC gun diagnostics beamline.

The beamline is equipped with adequate beam instrumentation and diagnostics enabling the above-mentioned studies: transverse phase-space characterization system (emittance measurement system), a scanning wire, various viewscreens, and a time-resolving deflecting RF cavity. The beamline is terminated by an aluminum beam dump capable of disposing 75kW beam power during high current operation.

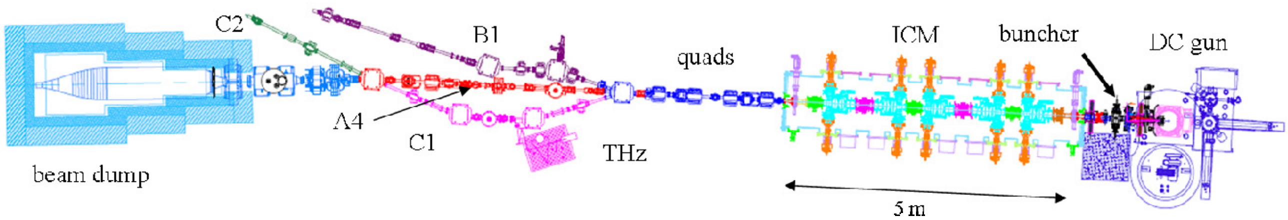

Figure 2: The layout of Cornell prototype ERL injector. Beam direction is to the left.

10 MeV Injector

Figure 2 shows the 5-15 MeV injector prototype. Various subsystems and their operational status have been detailed elsewhere [3]. The accelerator is equipped with a suite of interceptive beam diagnostics capable of assessing all 6 phase space dimensions, as well as the high average power compatible beam instrumentation, which includes two flying wire setups for transverse profile measurements and a THz spectrometer for longitudinal profile characterization. Only the beam instrumentation that does not require high average beam currents has been commissioned to date.

BEAM STUDY AREAS

On a fundamental level, the maximum beam brightness out of a photoemission gun producing short duration pulses is limited by the available accelerating gradient at the cathode and the transverse thermal energy of the emitted photoelectrons [4]. A number of additional measures are necessary in order to preserve the high brightness available from the photoguns, namely, controlling the space charge forces through appropriate laser shaping and external focusing downstream of the gun, gradual bunch compression in the injector without increase in the transverse emittance, understanding the effects of RF focusing and minimizing any emittance diluting effects arising from time-dependant nature of the RF fields.

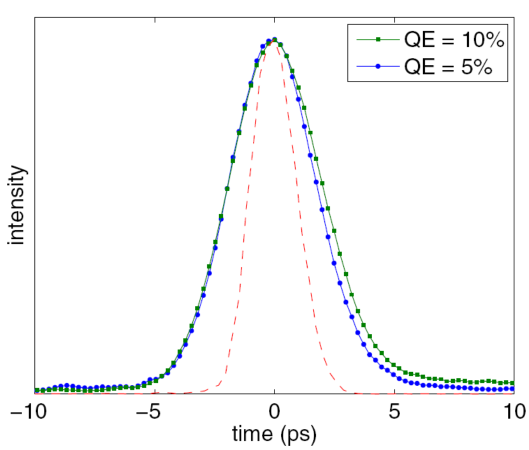

Figure 3: Temporal response obtained from GaAs excited by 1 ps rms 520 nm laser pulses. The dashed line shows the resolution of the measurement.

The merger section introduces the possibility of chromatic mixing in the space charge dominated beam, which may lead to additional emittance growth. Finally, the high average current effects, such as long range wakefields and ion neutralization of the beam, need to be understood and mitigated to realize a practical 100 mA ERL injector. An experimental program is underway to address beam physics questions arising in this class of high intensity low energy accelerators.

Photocathode Studies

Photocathodes are of paramount importance as their properties dictate operational characteristics, e.g. the laser wavelength and power required, the vacuum conditions, as well as set the limit on the smallest emittance or the shortest pulse duration achievable from the gun. We have conducted several studies of negative electron affinity photocathodes, namely, GaAs, GaAsP, and GaN, in which we have evaluated their potential as a photocathode of choice in the ERL photoinjector. Both the thermal energy and the response time have been measured in a wide range of laser wavelengths [5-6].

We find that GaAs remains the best material of the several candidates looked at by us so far. Nevertheless, from an operational point of view, an ideal photocathode yet remains to be realized. E.g. in the case of GaAs, despite its low thermal energy, we have observed a presence of a long photoemission tail depending on the laser wavelength and the quantum efficiency (QE) of the activated photocathode (see Figure 3). The quantum efficiency needs to be made lower on purpose (< 6%) during beam operation in order to avoid the tail and minimize beam losses in the accelerator.

Laser and Beam Shaping

The laser 3D distribution impinging on the photocathode must meet stringent requirements to realize the smallest emittance. The need to produce an electron beam distribution that linearizes the space charge forces in the gun vicinity leads to a desired laser distribution which for our parameters resembles a flattop longitudinally and an elliptical distribution transversely. Achieving the necessary laser intensity profiles together with the desired high efficiency of the shaping method represents an active area of research for the photoinjectors. We have demonstrated a simple and robust method of achieving the needed temporal profile through pulse stacking using a set of birefringent crystals [7] and performed the necessary characterization of the electron beam using a very low charge per bunch beam [8]. Figure 4 shows the result of the measurements showing both optical and electron beam measurements of the temporal profiles.

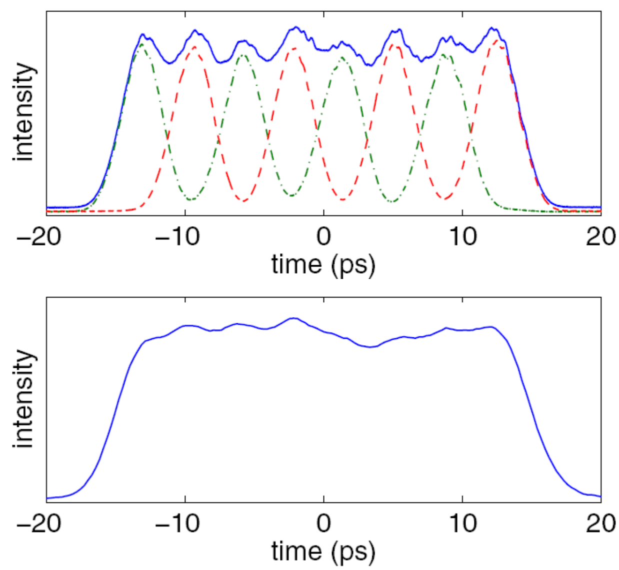

Figure 4: Laser pulse (top) and electron bunch (bottom) temporal profile measurement after three shaping crystals. Laser cross correlation shows the intensity of the two orthogonal polarizations (dashed and dot-dashed) and their sum (solid line).

The flattop transverse distribution can be generated using commercially available refractive shapers. However, our experience has shown that the very strict alignment requirements for this type of shapers cannot be easily met in our laser transport system and additional measures are required to stabilize the laser spot position for a steady output shape. A simple circular aperture is used in the meantime while the work continues in two directions: to stabilize the laser position and to explore more robust alternative methods of laser shaping.

Space-Charge Code Benchmarking

Space-charge dominated nature of beam dynamics in our injector leads to a highly non-linear behaviour and a need to rely on space charge modelling tools in order to find suitable optics solutions that provide the beam with the desired characteristics. Therefore, it is essential to establish the validity of space charge modelling tools used in design of the injector. A careful study was undertaken in the DC gun beamline where the number of variables controlling the beam dynamics is reduced to minimum. The results of this study are presented elsewhere [9]. Figure 5 shows the measured phase space distributions for two bunch charges: 80 pC and 20 pC. The measured transverse rms normalized emittance is 1.8±0.2 and 0.43±0.05 mm-mrad for the two cases respectively. Note the presence of a bright core in the beam, which is indicated by the core emittance and fraction values in the figure.

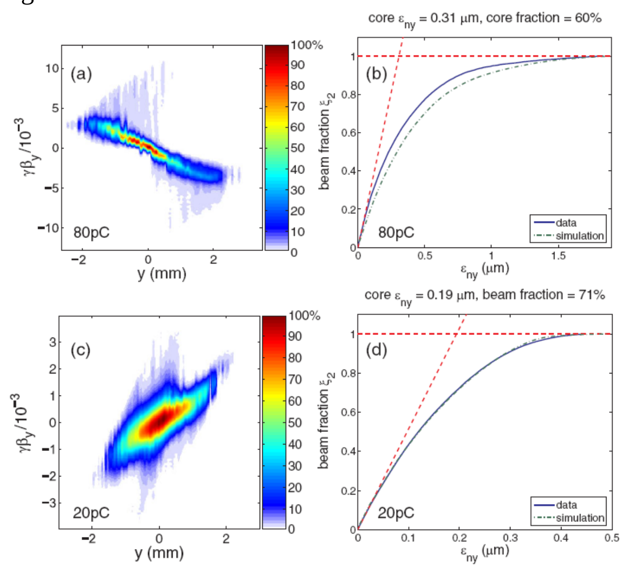

Figure 5: Measured (a), (c) transverse phase space after the gun and the corresponding emittance versus beam fraction curve (b), (d).

10 MEV INJECTOR COMMISSIONING

The 5-15 MeV injector has been in initial stages of operation for less than a year with several important instrumentation areas such as BPM system activated within this period. Work remains to be done in bringing the injector to its operational specifications, including an improved laser and an additional RF input coupler processing to reach 100 mA average beam current as well as generation of a stable beam with minimal losses. The commissioning plan seeks to address 4 different areas summarized below.

Linear Optics and Beam-Based Alignment

Despite the space-charge dominated nature of the beam dynamics in the injector, the first step in setting up the accelerator is to understand and control the beam orbit, a step that requires a firm grasp of linear optics. Furthermore, the emittance compensation process requires particular optics settings, which can be readily assessed and verified through beam orbit and response matrix measurements. Finally, a low emittance beam necessitates beam-based alignment in the optical elements to better than a millimeter requiring calculation and/or measurement of the relevant transfer matrix elements. The simulation tools for this purpose should include the ability to work with field maps for RF cavities, the DC gun, and overlapping solenoid fields, be lightweight and provide integration with the control system. Such tools have been developed and are starting to be used in the project [10].

Longitudinal Phase Space Dynamics

The beam in the injector undergoes bunch compression by about a factor of 6 due to the buncher cavity located after the gun and the 1st SRF cavity operated at a substantial off-crest angle. To minimize the emittance growth in the merger it is important to have beam with minimum energy spread entering the achromat. Additionally, it is important to cancel RF-induced emittance growth due to time-dependent focusing of the cavities, which can be accomplished through an appropriate choice of off-crest phases and gradients. Longitudinal phase space diagnostics, a key to meeting these specifications, has been successfully commissioned and proved indispensible in phasing the RF cavities. Nevertheless, we still have to demonstrate a robust procedure for setting up the buncher cavity and operating all five SRF cavities at their optimal (not on-crest) phases and gradients. Part of the challenge is due to non-ultrarelativistic beam energies in the beginning of the injector, which make the proper phasing dependent on the setting of the upstream elements.

Space Charge Emittance Measurements

The accelerator is equipped with two emittance measurement systems at the full energy (5-15 MeV), which allow direct measurements of transverse phase space distributions in both planes before and after the merger achromat section (B1 line in Figure 2). Achieving the maximum brightness as set by the photocathode thermal energy and the gun accelerating gradient requires a very high degree of space charge emittance compensation and RF-induced emittance growth cancellation. The beam diagnostics downstream of the cryomodule allows simultaneous mapping of 4D phase space variables (two transverse and two longitudinal variables, sections A4 and C2 in Figure 2), which should provide additional insights into the physics of emittance compensation. The merger section itself presents a number of challenges. Simulations show the emittance growth in this section to be a function of initial Twiss parameters and the energy spread. A series of measurements are planned to evaluate the effect of the merger on the transverse emittance and establish proper beam setup procedures that use a 4-quad telescope found downstream of the cryomodule and the lenses inside the merger.

Because the thermal load difficulties have been encountered with the full repetition rate laser system (1.3 GHz, maximum power demonstrated is 7 W with 20 W being the goal specification) and because none of the diagnostics being used in direct phase space measurements can handle more than about 1 kW of beam power, a second laser system operating at 50 MHz has been constructed, which has all the desired single bunch properties. The duty factor of the pulse train from this laser is further reduced by passing it through a Pockels cell: this pulse train will be used in the experiments requiring the full bunch charge beam. The 50 MHz laser will be operated interchangeably with the 1.3 GHz laser system switching between the pulsed full charge beam running and the continuous 1.3 GHz train required for reaching the high average current.

High Average Current Phenomena

Operating the full beam current requires mature understanding and control of both the orbit and beam envelope in the space charge dominated regime. Good operational stability of various subsystems is necessary to realize low loss running necessary for good lifetime of the photocathode. There are several outstanding questions with regard to the high average beam running operation, namely, the ion neutralization of the electron beam, which will lead to significant changes in the betatron phase advance experienced by the beam, and the effect of the long-range wakefields on a 1.3 GHz train of 77 pC bunches. Simulations suggest that the ion effect will be particularly significant and may require additional measures such as clearing electrodes for reliable beam operation. Finally, the accelerating RF structures at 100 mA will operate with a very strong coupling and the corresponding changes in the field distribution in the input coupler region may introduce asymmetric quad-like RF focusing fields. This effect will need to be characterized prior to demonstrating 100 mA current out of the injector.

HIGH CURRENT STATUS

Reliable production of 100 mA represents a major challenge for high-brightness photoinjectors. Our experience and that of other laboratories suggest that maintaining excellent vacuum inside the gun is a key to obtaining a good lifetime out of the photocathode. The operation with DC laser in the gun diagnostics beamline has allowed us to achieve 20 mA average current. The current in this case was limited by the gas backstreaming from the aluminium dump located about 5 m from the gun. The correlation between the gun vacuum and the photocathode lifetime that we observed confirms the notion of the ion-backbombardment being the primary mechanism which limits the lifetime of photocathodes in this type of systems.

The 5-15 MeV accelerator has so far achieved 4 mA of average current as limited by the radiation losses limit set for personnel protection in the experimental area (which shares the floor with CHESS user stations). Several of the challenges for producing stable beam included an excessive HV power supply ripple which led to beam losses during the high average current operation. Since then, modifications in the HV power supply resulted in voltage peak-to-peak variations of about 150 V over the bandwidth of 1 kHz at low average current (few mA) operation. Additional work is needed to ensure stable operation of the HV power supply at higher currents.

ONGOING WORK

Investigations of the beam orbit inside the injector cryomodule have revealed the presence of stray magnetic fields which lead to excessive beam losses and thwart beam-based alignment methods when the RF fields are off, or when the cavities are being turned on one by one. Further evaluation of these stray fields showed that they lead to intolerable emittance growth even when RF is on due to a strong sextupole-like component present inside the cryomodule. The work is underway to open the cryomodule, locate and eliminate the source(s) of unwanted magnetic fields.

So far we have been operating the beam with a low voltage in the DC gun after having experienced problems with field emission and ceramic puncture. Having no spare ceramic, the gun voltage has been limited to a conservative value of 250 kV despite having momentarily reached over 425 kV during high voltage processing. A parallel effort of procuring bulk resistivity ceramic has been underway for over a year, as well as designing a segmented insulator suitable for a 750 kV gun. A dedicated gun setup is necessary to allow improvements while at the same time continuing beam running in the 5-15 MeV accelerator. These improvements are planned as a part of the next stage of the injector prototype effort.

CONCLUSION

The injector prototype at Cornell has been producing beam for about 1.5 years in the DC gun commissioning beamline (September 2006 till March 2008), and for about 10 month after the completion of the 5-15 MeV accelerator since July 2008. A number of beam experiments have been performed to address outstanding questions of space charge characterization, photocathode physics, and the high beam brightness production out of the photogun. An active commissioning effort for the 5-15 MeV injector is still underway to resolve a number of problems discovered during the initial beam operation. Additional improvements to the gun, the laser, as well as the beam experimental program have been proposed as a part of the next stage in the ERL injector development project to demonstrate beam specifications required for the ERL light source of hard x-rays.

ACKNOWLEDGEMENTS

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