FIRST TESTS OF THE CORNELL UNIVERSITY ERL INJECTOR*

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Abstract

Cornell University is planning to build an Energy Recovery Linac (ERL) X-ray facility. For an ERL, it is well known that the x-ray beam brightness for the users is mainly determined by the initial electron beam emittance provided by the injector. To address technical challenges of producing very low emittance beams at high average current as required for an ERL, Cornell University has proposed a prototype injector with 5-15 MeV beam energy, 100 mA maximum average current and 77 pC/bunch. In this article, we describe the design, construction and initial results for an ERL injector prototype now under operation.

INTRODUCTION

An electron injector for an ERL has many challenges. To provide the x-ray beam quality that users demand for the future, the injector needs to meet the requirements show in Table 1 [1].

Table 1: Injector Requirements (values in ( ) are goals for the prototype system of this paper)

Beam Energy	10-15 (5-15) MeV
Charge per bunch	77 (77) pC
Average Current	100 (100) mA
Bunch Length	2-3 (2-3) ps
Transverse Emittance	0.3 (2) µm
Operating Frequency	1.3 (1.3) GHz

At Cornell University, we have undertaken a program to develop and test such an injector (see Fig. 1) towards realization of this difficult set of requirements. The design was based on detailed simulations using genetic algorithms to find the optimum solutions to the multi-parameter design space [2]. The electron source is a DC photoemission gun using a GaAs cathode, providing a 1.3 GHz bunch train of 77 pC/bunch with a 20-40 ps 'beer can' distribution. This is followed by a short section for emittance compensation solenoids and a normal conducting buncher cavity [3]. The beam is then accelerated through a cryomodule containing five 2-cell niobium superconducting RF (SRF) cavities, each with individual control of phase and gradient. The cavities have two opposing 50 kW input couplers to feed in 100 kW per cavity. The available RF power allows for either 100 mA at 5 MeV or 33 mA at 15 MeV. After the SRF cavities, an extensive suite of diagnostics allows for a complete characterization of the transverse and longitudinal phase space of the beam. The beam is terminated in an aluminum dump with a capacity for disposing 600 kW of average power.

Each section of the injector will be described in detail, along with the current status of commissioning and beam tests.

DC PHOTOEMISSION GUN

Based on the experience of other labs [4] and of the authors, DC photoemission guns provide the best chance of producing the low emittance, high average power beam to meet the needs of an ERL. The present record for average current belongs to the Boeing normal conducting RF (NCRF) gun [5] at 32 mA (25% duty factor), and while other projects continue to push for higher current with NCRF guns, no improvements have been realized. Work on SRF guns has made excellent progress recently [5], but the prospect of obtaining 100 mA average current is still many years away. The DC gun used for the Jefferson Lab FEL project [4] has reliably provided 135 pC bunches at an average current of ~9 mA, and an extension of that technology is the most likely path to meet the needs of an ERL injector in the near future.

High Voltage Gun

Common sense dictates that high initial beam energy and high electric field at the cathode are necessary to overcome the space charge forces in bunched beams and obtain the best possible emittance. Simulations [2] show that higher gun voltage is important for obtaining low emittance up to a certain point, after which the improvement is relatively small. Thus, a DC gun operating in the range of 500-600 kV should meet the emittance goals with the appropriate cathode. To minimize dark current at the operating voltage, the gun must be processed to roughly 25% above the operating value, consequently the Cornell gun has been designed to withstand 750 kV maximum voltage.

A schematic cutaway of the Cornell DC photoemission gun is shown in Fig. 2, and was designed to meet the requirements in Table 2. The gun was operated for over a year using a test beamline to measure the performance of the gun and cathode before mating it to the rest of the injector. Details of these measurements have been published elsewhere [7, 8], with the main result that the emittance measurements at 77 pC/bunch and 250 kV beam energy match the simulations very closely, giving confidence that the simulations for the entire system are valid. Two difficulties observed involved the laser profile and laser stability. Tails in the phase space distribution were traced (through simulation) to non-uniformities

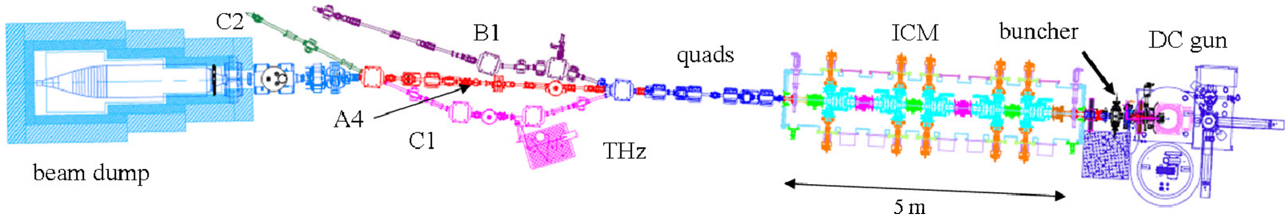

Figure 1: The layout of the Cornell prototype ERL injector.

across the 'flat-top' laser distribution and variations in the distribution over time. The pointing stability of the laser at the cathode was also an issue, causing jumps in the phase space measurements. The laser itself is stable to 20-30 μm rms, but this increases upon demagnification to the cathode. We have since purchased an active position stabilization device (MRC Systems GmbH) which will reduce the position jitter at the cathode to < 10 μm rms.

Table 2: DC Gun and Laser Requirements

Operating voltage	500-600 kV
Maximum voltage	750 kV
Average Current	100 mA
Vacuum during operation	$< 1\times10^{-11}$ Torr
External SF_6 pressure	4 atm
Laser wavelength	520 nm
Laser pulse shape	'beer can'
Laser pulse length	20-40 ps
Phase jitter	< 1 ps

All guns of this type suffer from the problem of controlling field emitted electrons from the high voltage surfaces. These electrons can land on the insulator, and if the charge builds up punch-through can occur, causing a vacuum leak. We purchased an insulator with an internal resistive coating (CPI, Inc.) to bleed off these electrons, but it has only been successful up to 450 kV during processing, above which punch-throughs occur. In addition, the coating has not adhered well, leaving a layer of dust on the electrodes, certain demise for reaching 750 kV. Colleagues at Daresbury Lab [9] have built an insulator using a new material from Morgan Advanced Ceramics (AL-970CD) which is more resistant to field emitted electrons, at least up to 500 kV. We are in the process of obtaining a new insulator using this material, and are also investigating the use of segmented insulators [10] which completely block the line of sight between the electrodes and the insulator, but have a much more complicated mechanical structure. For now, we are limiting the gun voltage to 300 kV to reduce the chance of damage, until a spare is obtained.

If one can make electrodes that do not field emit, the insulator design is not so important – this is the Holy Grail for gun design (and for SRF cavities). We have built the present gun emulating the best techniques known for cavity cleaning, namely electro-polishing followed by high pressure rinsing. In a test chamber, gradients of 30 MV/m have been routinely reached on large area electrodes, but these results have not been reproduced in the real gun, most likely due to dust contamination from the insulator coating.

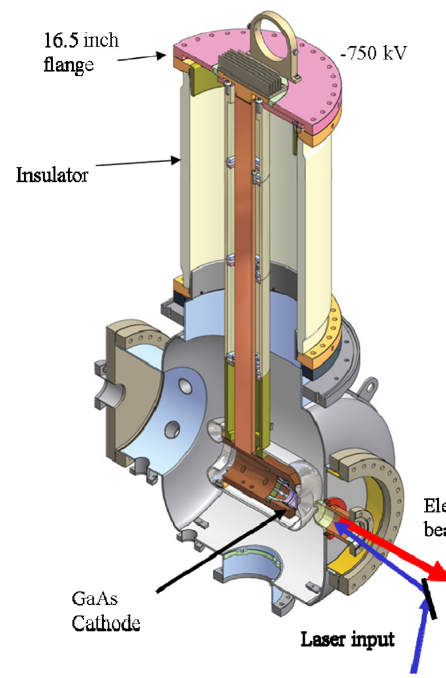

Figure 2: The Cornell Photoemission Gun.

Laser System

To produce 100 mA from a GaAs cathode with a 1% QE, over 20 Watts of laser power at 520 nm is required at the cathode (2 W for 10% QE). Accounting for possible losses in the laser transport and beam shaping, a laser with 40 W of average power is desired. The system must provide pulses at a repetition rate of 1.3 GHz synchronized to the RF master clock (with a timing jitter < 1 ps), and a configurable pulse shape in time and space for minimizing the electron beam emittance.

We have chosen to use a Yb-doped fiber laser system to meet these requirements. Initially, the oscillator was made in-house, but difficulties were encountered in accurately synchronizing it to the RF system.

Subsequently, a commercial fiber laser 'clock' was purchased from PriTel Inc. They modified a standard product to work at our pulse repetition rate. The laser is triggered by the RF master clock signal, and the jitter between the output pulse the clock signal is less than 500 fs. The pulses are fed to a single mode fiber amplifier where the pulse energy is boosted to 150 nJ, low enough to prevent any nonlinear distortion. The pulse energy is further increased through amplification in a double clad large mode area fiber amplifier built to work in nearly single mode regime. Currently we have implemented only one such stage and achieved average power of 35 watts at 1040 nm (27 nJ pulse energy). The IR pulses are frequency doubled in a LBO crystal to produce pulses centered at 520 nm and energy of 9 nJ (12 W average power). Additional thermal management is needed to reach higher powers. Laser shaping of the pulses has been described in detail elsewhere [11].

Photocathode Materials

A perfect photocathode for an accelerator electron source would have high efficiency at a convenient laser wavelength, fast response time, long lifetime and a low thermal emittance. Unfortunately, no such cathode exists today, although the search continues. A number of different photocathodes meet some of these criteria, so tradeoffs have to be made depending on the requirements of the particular system. For an ERL, obtaining 100 mA average current means high quantum efficiency (QE) photocathodes are a necessity.

Semiconductor photocathodes are currently the best choice for high QE and low emittance. Examples are GaAs, Cs_2Te, GaN, and K_2CsSb. Both Cs_2Te and GaN show promise but require UV light but there are no laser systems available to produce enough average power in the UV. Both GaAs and K_2CsSb have 5-10% QE for ~520 nm light, where high average power lasers are readily available. At Cornell, we have chosen to use GaAs, but are still considering other cathodes depending on the application.

As mentioned earlier, it is possible to recover the intrinsic thermal emittance from the cathode using a carefully designed emittance compensation scheme for the bunch charges of interest to an ERL [2]. Of all the cathodes available, GaAs has the lowest thermal emittance [6], so is the cathode of choice for an ERL. Unfortunately, the QE is near a minimum when the thermal emittance is smallest (close to the band gap), thus unsuitable for high average current. In addition, it is well known that at ~780 nm a fast laser pulse will generate an electron beam with a 20-40 ps tail, which is not acceptable for low emittance operation. For shorter wavelengths (~520nm) recent measurements [9] show that the response time is quite fast (~1 ps) as long as the QE is not too high (< 10%). This points out some of the tradeoffs one has to make even when using GaAs, and we have chosen an operating wavelength of 520 nm as the best compromise between QE, thermal emittance and response time.

The last important parameter is cathode lifetime. The cathodes described above are all sensitive to chemical poisoning to some extent, and require ultra-high vacuum. GaAs is the most sensitive, unfortunately, requiring vacuum levels < 10^{-11} Torr for successful operation. An additional lifetime limiter is ion back-bombardment which further reduces QE. The electron beam can ionize residual gas molecules anywhere along their path, which can then be accelerated back towards the cathode surface. Jefferson Lab [12] has carried out extensive measurements at 10 mA average current, and has measured cathode lifetimes as high as 10^6 C/cm^2 (the amount of charge extracted per cm^2 when the QE has fallen by 1/e). One can use this data to estimate that a 10 W maximum power laser system should be able to provide 100 mA over 100 hours with a 1.8 mm diameter laser spot [13]. Such performance has not be demonstrated yet, and it is certainly an optimistic estimate.

SRF AND RF SYSTEMS

There are many challenges in constructing an injector for an ERL, one of the most difficult being an injector cryomodule (ICM). The ICM RF system must transfer up to 500 kW to the beam (for the prototype system), damp out significant higher order modes (HOM) up to tens of GHz, and preserve the low emittance generated by the electron source. The specifications for the ICM RF system are shown in Table 3.

Table 3: Specifications of the ICM RF system

Parameter	Value
Number of cavities	5
Accelerating voltage per cavity	1 – 3 MV
2-cell cavity length	0.218
R/Q (linac definition)	222 Ohm
Q_{ext}	$4.6\times10^4 – 4.1\times10^5$
RF power per cavity	100 kW
Maximum useful klystron power	≥120 kW
Amplitude stability	9.5×10^{-4} (rms)
Phase stability	0.1° (rms)

The five 2-cell cavities were built at Cornell and vertical tested with $Q_0 > 1\times10^{10}$ at 15 MV/m and lower. One cavity was built into a horizontal test cryostat along with HOM loads [14] to verify the construction techniques before building the final ICM. The initial Q of the cavity was only 1×10^9, much lower than the vertical test results. On disassembly it was discovered that one of the ceramic HOM tiles had cracked and fallen, creating dust that reduced the cavity performance. The faulty tiles were removed and replaced with different material, then extensively cold tested before installing in the main ICM. Twin, opposing input couplers have been tested up to > 60 kW average power, more than the 50 kW needed for 100 mA operation. A complete description of the cryomodule construction and testing can be found in references [15,16] (see Fig. 3).

Figure 3: The ICM after final assembly.

So far all ICM operations have been at 1.8 K. The cavities have been processed in pulsed mode to >15 MV/m, and in all cases but one the limit was due to vacuum activity in the input couplers, so further processing should improve the maximum field. Cavity 4 quenched in pulsed mode (2 ms long pulses, 20 ms period) at 18 MV/m. In CW mode all cavities reached >2.8 MV/m when powered individually (see Table 4). Operation of cavity 1 was limited by excessive RF losses due to field emission (FE). While cavity 2 was limited by the input coupler vacuum, it also had rather significant FE. Operating at 1.8 K with two pump skids, the cryogenic system can handle all five cavities at gradients up to 10.4 MV/m (2.4 MV per cavity). Raising temperature to 2 K will allow for an increase of the cryogenic system heat handling capacity and hence higher gradient ICM operation.

Table 4: Cavity Performance Summary (IC = input coupler vacuum)

Cavity	CW	Limit	Pulsed	Limit
1	2.8 MV	Cryogenics	4.35 MV	IC
2	2.9 MV	IC	3.75 MV	IC
3	3.5 MV	Cryogenics	3.66 MV	IC.
4	3.4 MV	Cryogenics	4.15 MV	Quench
5	3.5 MV	none	5.20 MV	IC
All 5	2.4 MV	Cryogenics		

CRYOGENIC SYSTEM

The ICM requires cryogen delivery at three different temperatures: 1.8-2 K, 4-6 K, and ~80 K. The RF cavities are submerged in 1.8 K superfluid; supercritical helium streams at 4-6 K and 80 K intercept heat conducted down the internal supports from room temperature, as well as heat generated in the RF input couplers and higher-order-mode RF absorbers. The mass flow of 5-10 g/s is supplied by one of the helium compressors.

The helium refrigerator has no built-in capability to produce the superfluid liquid that cools the RF cavities. Instead, liquid from the 4.2 K pot is passed through a heat exchanger where it is pre-cooled by the low-pressure gas boiled off in ICM. It then goes to a JT valve where it is throttled to the 12 Torr pressure corresponding to 1.8 K liquid helium temperature. A 2 K heat exchanger greatly reduces the gas fraction of the stream emerging from the JT, and hence, the mass flow seen by the pump used to maintain the 12 Torr pressure above the 1.8 K liquid. The low-pressure gas is heated to near room temperature before being sent to the Roots blowers, the input stage of our pumping system. The 12 Torr pressure can be controlled to ± 0.01 Torr by means of a variable frequency (VFD) drive to the blower motor.

Heat absorbed at 1.8 K is a liquefaction load, since minimal use is made of the return gas. Thus, 1 g/s (~30 L/hour) boiled off there corresponds to about 20% of the capacity of one of the refrigerators. Our current estimate of the static heat load at 1.8 K is 10±3 Watts, complicated by the presence of a thermal oscillation associated with the cool-down plumbing.

DIAGNOSTICS

The three diagnostics beamlines after the ICM are shown in Fig. 1. A matching section consisting of four quadrupoles resides between the ICM and the beamlines. Each beamline has a specific purpose along with the appropriate diagnostics to allow a full characterization of the beam phase space. Some of the diagnostics are only capable of handling 1-2 kW and thus must be used with pulsed beam (made by chopping the laser with a Pockels cell), while several of the devices can be used with the full beam power.

In the straight section (A4), a pair of slits with scanning magnets followed by a Faraday cup is used for transverse phase space measurements. An RF deflection cavity [17] downstream provides bunch length measurements with sub ps accuracy. By observing on a viewscreen at the end of the C2 line after a dipole, one can observe the time-resolved energy spread of the beam, or study slices of the beam in conjunction with the slits.

The B1 line geometry is similar to a method for merging the beam from the injector into the main ERL linac. After passing through the 3 dipole arrangement, another pair of (identical) emittance measurement slits allows for the measurement of the transverse phase space. This can then be compared to the straight ahead measurements to study the emittance growth in mergers. Other merger schemes can easily be studied.

The chicane (C1) line has several high power diagnostics as well as a viewscreen for cavity phasing. After the second dipole in the chicane, a copper mirror deflects THz radiation into an interferometer which can be used to monitor the bunch length [18]. In the straight arm, a custom made 'flying wire' that can handle the full beam power is available for beam size measurements. There is a similar flying wire in the A4 section. The high power diagnostics are meant for studying the beam properties under the influence of ions, wakefields, HOM's in the cavities and other high power RF effects.

Strip-line beam position monitors are used all along the beamlines to provide ~10 µm resolution.

BEAM DUMP

The beam dump for the Cornell injector is based on a SLAC klystron collector [19] and is designed to absorb up to 600 kW average power for beams between 5 and 15 MeV. The beam is defocused using a pair of strong quadrupole magnets and rastered in a circle to reduce the instantaneous power on the dump walls. It is made using aluminum instead of the copper to reduce neutron production. The dump is made of two sections: the body and a outer shell to contain the cooling water. The body is 20 mm thick and the shell is 13 mm thick, with the total thickness enough to stop the beam. The sections are e-beam welded together and the welds are inspected for voids and cracks. The interior shape of the cone was designed using GEANT to distribute the scattered electrons (and thus the heat) as uniformly as possible around the cooled surface. A flow of 60 gpm is sufficient to extract ~40 W/cm^2 with a 600 kW heat load.

Metalex Mfg, Inc (Cincinnati, OH) is building the beam dump and delivery is expected at the end of September, 2008. It will be installed upon arrival along with extensive shielding.

COMMISSIONING RESULTS AND PLANS

The entire injector has been installed with the exception of the high power beam dump, whose delivery is imminent. The gun has been processed only to 300 kV (as described earlier) so far, and we are not pushing the voltage higher until a backup insulator is acquired. The buncher cavity has been processed to ~50 kV peak voltage, limited by multi-pacting in the tuner area, which will be fixed by a new TiN coated tuner. The SRF cavities have been processed as described earlier, well enough to reach 12 MeV beam energy at 1.8 K, or 15 MeV at 2 K.

Beam has been accelerated to over 5 MeV so far, and threaded through each of the diagnostics beam lines. Initial checkout of the BPM's and the various diagnostics are just underway. Qualitatively, the phase stability between the laser and the RF is quite good as evidenced by a stable beam on the chicane (C1 line). The maximum current so far has been 20 µA, limited by the radiation shielding and the delivery of the final beam dump.

The near term plans include completing commissioning of the BPM's and other diagnostics, installing the final beam dump and shielding, testing the machine protection system and increasing the laser power. Once that is done an extensive set of phase space measurements will begin along with the push for 100 mA.

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