READINESS FOR THE CORNELL ERL*

G. H. Hoffstaetter†, A. Bartnik, I. V. Bazarov, D. H. Bilderback, M. G. Billing, J. D. Brock,
J. A. Crittenden, L. Cultrera, D. Dale, J. A. Dobbins, B. M. Dunham, R. D. Ehrlich,
M. P. Ehrlichman, R. Eichhorn, K. D. Finkelstein, E. Fontes, M. J. Forster, S. Full,
F. Furuta, D. Gonnella, S. W. Gray, S. M. Gruner, C. Gulliford, D. L. Hartill, Y. He,
R. G. Helmke, V. Ho, R. P. Kaplan, S. S. Karkare, V. O. Kostroun, H. A. Lee, Y. Li, X. Liu,
M. U. Liepe, L. Cultrera, C. E. Mayes, J. M. Maxson, A. A. Mikhailichenko, H. S. Padamsee,
R. Patterson, S. B. Peck, S. E. Posen, P. G. Quigley, P. Revesz, D. H. Rice, D. C. Sagan,
J. O. Sears, V. D. Shemelin, D. M. Smilgies, E. N. Smith, K. W. Smolenski, A. B. Temnykh,
M. Tigner, N. R. A. Valles, V. G. Veshcherevich, A. R. Woll, Y. Xie, Z. Zhao,
CLASSE, Cornell University, Ithaca NY 14853 USA

Abstract

Energy-Recovery Linacs (ERLs) are proposed as drivers for hard x-ray sources because of their ability to produce electron bunches with small, flexible cross sections and short lengths at high repetition rates. Cornell University has pioneered the design and hardware for ERL lightsources. This preparatory research for ERL-lightsource construction will be discussed. Important milestones have been achieved in Cornell's prototype ERL injector, including the production of a prototype SRF cavity that exceeds design specifications, the regular production of long-lived and low emittance cathodes, the acceleration of ultra-low emittance bunches, and the world-record of 65 mA current from a photoemission DC gun. We believe that demonstration of the practical feasibility of these technologies have progressed sufficiently to allow the construction of an ERL-based lightsource like that described in Ref [1].

INTRODUCTION

The promise of Energy-Recovery Linacs for hard-x-ray sources has been recognized early on, and several labs have therefore proposed to build ERL-based light sources. But before a large-scale light source could be built, several important milestones needed to be achieved. The National Science Foundation therefore has been funding Cornell University since 2005 to verify that the required beam currents, small emittances, sufficiently long cathode lifetimes, and SRF cavities with sufficiently low losses can be produced.

On all these fronts, major milestones have been achieved: 65 mA beam currents [2] have surpassed the previous world record by a factor of two; the 90% x/y-emittance has become so small that an acceleration to 5 GeV would lead to 51/29 pm for 77 pC bunches and 23/14 pm for 19 pC [3]. With 1.3 GHz bunch repetition, this 5 GeV beam could drive a hard-x-ray source with a brightness that is about 20 times larger than the brightest beam today (at PETRA-III [4]). The measured cathode lifetime of more than 30 hours for 60 mA operation allows for sufficient intervals between cathode replacements. Furthermore, it was important to show that the proposed operations cost of an ERL can be achieved, much of which is for cooling the SRF cryo-system. Cornell produced an ERL 7-cell cavity with a quality factor larger than the specified $Q_0 = 2 \times 10^{10}$. This would allow the ERL lightsource to operate at about a 15 MW cryo-system load.

Achieving these milestones has moved ERL technology to a stage where a large-scale light-source project could start. The Project Definition Design Report of the Cornell ERL [1] outlines a full ERL design and its engineering needs.

HIGH CURRENT

The Cornell ERL injector was designed to provide 100 mA average current at a 1.3 GHz repetition rate, corresponding to a bunch charge of 77 pC. The prototype injector has 500 kW of RF power available, thus has the capability to run 100 mA at 5 MeV, or lower current at energies up to 15 MeV. Recently, this system reached an average current of 65 mA [2], surpassed the long-standing record of 32 mA set in 1993 [5].

There are many challenges in constructing a photo injector for an ERL, including: (1) robust, high quantum efficiency (QE) photocathodes; (2) controlling halo particles; (3) a stable, high-average power laser; (4) RF system.

To generate 100 mA from a 1% QE photocathode requires approximately 20 W of light at 520 nm, or 2 W for a 10% QE cathode. The laser repetition rate must match the RF frequency and be synchronized to the RF master clock, which is 1.3 GHz for this machine. The laser used here [6] starts with a commercial fiber oscillator that generates the seed pulses. This is followed by two preamplifier stages and one main amplifier stage, all using Yb gain fiber. Up to 65 W at 520 nm have been obtained, providing more than enough light to reach 100 mA with overhead for opti-

---

* Supported by NSF award DMR-0807731 and NY State

† gh77@cornell.edu

cal transport losses, laser shaping, and feedback. The laser pulse shape is controlled in both the transverse and longitudinal planes to produce a 'flat top' profile.

The RF system must transfer high average power to the beam, damp significant higher order modes (HOM) up to tens of GHz, and preserve the low emittance generated by the electron source. For our prototype, 500 kW of available RF power limits the maximum energy at full beam current.

LONG CATHODE LIFETIME

Cathodes for high average current systems must have good QE (1-10%) at a convenient wavelength (520 nm, for example), have good lifetime, be able to withstand vacuum bursts, have fast response time (a few ps or better), and have low thermal emittance. The cathode material that comes closest to meeting these requirements are the alkali antimonide family, commonly used in photomultiplier tubes. Some examples are $\mathrm{CsK_2Sb}$, $\mathrm{NaK_2Sb}$, and $\mathrm{Cs_3Sb}$ [7, 8]. GaAs [9] is also used in a number of guns, as it has the potential to produce beams with the lowest thermal emittance, but its sensitivity to vacuum and vacuum bursts make it a poor choice, especially during machine commissioning. A major issue with using any photocathode for high average currents is damage due to ion back-bombardment. Ions are generated along the path of the electron beam from collisions with the residual gas, and are accelerated back towards the cathode with energies ranging from a few eV up to the accelerating voltage of the gun. At high currents, the damage occurs quickly, leaving the center of the cathode unusable. To combat this, we only activate a small area of the cathode, away from the center where ion damage occurs.

Using a $\mathrm{CsK_2Sb}$ cathode, 60 mA was sustained for 25 minutes, during which the cathode QE decayed with a 30 hour $1/e$ lifetime. This is sufficient for continuous duty operation with a the expected 15 minute per day photocathode regeneration cycle.

SMALL EMITTANCES

Recently, low emittance measurements were performed in the merger section of the injector. The settings of the machine for these measurements were determined using a multi-objective genetic algorithm and a complete model of the injector with the 3D space charge code GPT [10]. Two optimized settings were eventually generated corresponding to 19 and 77 pC per bunch. Loading these settings into the machine, and using a 50 MHz laser system to limit the beam power hitting the interceptive emittance measurement systems, the normalized horizontal and vertical projected phase spaces were directly measured at both bunch charges, and the normalized emittances computed. In addition, the time-resolved horizontal phase space was measured. From this the bunch current profile and rms bunch length were measured. All measurements were taken at 8 MeV.

In the horizontal plane, the measured projected normalized emittance at 19 (77) pC per bunch was 0.23 (0.51) mm-mrad for 90% beam fraction and 0.14 (0.28) for the core beam fraction, in this case 67 (64)%. In the vertical direction, the corresponding values were 0.14 (0.29) mm-mrad for 90% beam fraction, and 0.09 (0.19) mm-mrad for the core fraction, in this case 70 (70)%. These values should be compared to the measured values of the thermal emittance in each plane. In both planes, the thermal emittance was for these settings was 0.12 (0.24) mm-mrad. The quoted core emittances in the horizontal plane are thus dominated by the thermal emittance. In the vertical plane, both the 90% and core emittances are dominated by the thermal emittance value. All of these emittances were measured with an rms bunch length of $\leq 3\,\mathrm{ps}$, and with an rms energy spread on the order of 10^{-3}.

If accelerated to 5 GeV, the normalized horizontal emittances would give a corresponding geometric emittance of 24 (52) pm and 14 (29) pm for 90% and core beam fractions at 19 (77) pC per bunch, respectively. In the vertical plane, the corresponding geometric emittances would be 14 (30) pm and 9.2 (19) pm for the 90% and core beam fractions at 19 (77) pC per bunch. These values should be compared with the horizontal emittance found in third generation light sources such as APS: 3 nm (effective) at 7 GeV, [11], and PETRA III: 1 nm at 6 GeV, 100 mA [4].

Detailed simulations [1, 12] show that improvements to the photoinjector can reduce the emittances even further by roughly a factor of 3, resulting in about 10 times higher beam brightness.

LOW ENERGY LOSS IN CAVITIES

The SRF properties of a 7-cell main Linac cavity were characterized at several stages before completing the assembly of a fully equipped horizontal test cryomodule (HTC). The purpose of measuring the cavity properties at intermediate stages was to both qualify the assembly process as well as understand the contribution of each stage to the overall quality factor Q and higher-order mode properties. Qualification proceeded in four stages: 1) Vertical testing of the cavity; 2) horizontal test with axial RF input coupler (HTC-1); 3) horizontal test with side mounted high power RF input coupler (HTC-2); and 4) test with high power RF input coupler and beam line HOM loads (HTC-3). More details about these tests are available in other papers [13, 14, 15], with the results quoted here.

The cavity Q was measured by standard RF methods in a vertical dewar at 1.6, 1.8 and 2.0 K. The cavity reached 26 MV/m (limited by available RF power), and met the Q specification. Following the successful vertical test, while maintaining a clean RF surface, the cavity was outfitted with a helium jacket, and installed in a horizontal test cryomodule in the HTC-1 experiment. For this run, the same axial RF coupler used in the vertical test was left on the cavity, and used to measure the Q of the cavity via RF methods.

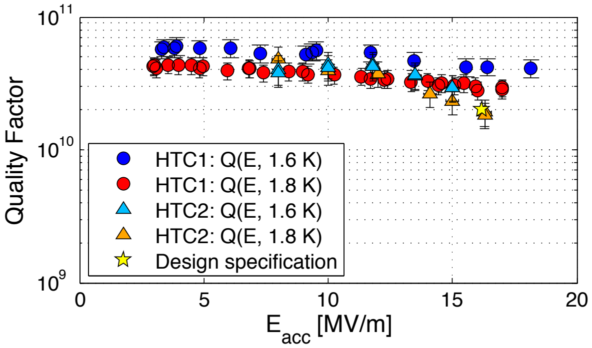

Figure 1: Plot of the quality factory vs. accelerating gradient of the prototype 7-cell cavity after thermal cycling.

Additionally, the Q was measured via cryogenic methods. This was necessary because HTC-2 and HTC-3 use high power RF couplers that are strongly over-coupled, making standard RF determinations of Q inaccurate. The two methods of Q measurement agreed, and in HTC-1, after thermal cycling, gradient and quality factor measurements exceeded design specifications, reaching 3.0×10^{10} at 1.8 K, and a record 6×10^{10} at 1.6 K and 5.0 MV/m.

HTC-2 incorporated the side mounted high power RF input coupler to the HTC-1 assembly. The Q at design gradient and temperature were met the 2×10^{10} goal after thermally cycling the cryomodule above 15 K. The quality factors from these tests are presented in Fig. 1. With the successful HTC-1 and HTC-2 tests, two beamline higher-order mode absorbers were installed for the HTC-3 run. Initial measurements show quality factors consistent with the pre-thermal cycled values from the previous HTC experiments, and suggest successful broadband damping of higher order modes [15].

MAIN-LINAC CRYOMODULE PROTOTYPE

Based on the encouraging results from the horizontal test cryomodule (HTC), the design and construction of the ain-Linac cryomodule was started. The module will house 6 superconducting, 7-cell cavities, fully equipped with tuners, couplers and HOM absorbers (one on each side of a cavity) as well as a focusing/corrector unit [16]. The design of the module, shown in Fig. 2 has been completed. Meanwhile, 3 out of the 6 cavities have been built and are currently tested vertically. Other major components have been ordered (e.g. vacuum vessel, couplers etc). String assembly will start early summer and we plan to have completed by the end of 2014.

This module will allow studying the high Q performance with significant statistics (6 cavities) and confirm the figures set for microphonics and RF power. It also allows verification of the cost drivers of the full ERL, as well as checking the x-ray background produced by its dark current which highly impacts the tunnel design and shielding of electronics.

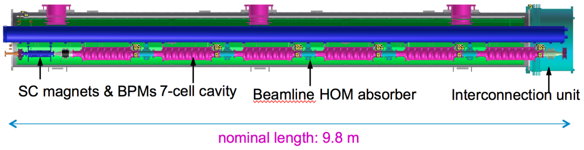

Figure 2: Cross-section of the 10 m long main-Linac cryomodule prototype housing 6 cavities, fully equipped for beam operation, currently under fabrication.

CONCLUSION

Cornell University has achieved important milestones for the construction of ERL light sources: world-record currents from a photoinjector; ultra-small emittances; SRF cavities with low RF losses; and long-lived photocathodes. We believe that these technologies have sufficiently progressed years to allow the construction of an ERL-based lightsource. As for any large accelerator project, engineering challenges remain, many of which can be addressed by an ERL test loop for which Cornell already would have all major components available: gun, injector Linac; ERL cryomodule; and beam stop. Suitable space is also available and Cornell is ready to begin construction of such a test loop if funding were available.

REFERENCES

[1] G. H. Hoffstaetter, S. Gruner, M. Tigner, *eds.*, Cornell ERL Project Definition Design Report (2011) `erl.chess.cornell.edu/PDDR`

[2] B. Dunham et al., App. Phys. Lett. **102** 034105 (2013).

[3] C. Gulliford et al., arXiv:1304.2708 (2013)

[4] K. Balewski et al., “PETRA III UPGRADE,” Proceedings of IPAC2011 THPC020 p. 2948

[5] D. H. Dowell et al., Appl. Phys. Lett. 63, 2035 (1993).

[6] Z. Zhao et al., Optics Express **20** (5), 4850 (2012).

[7] I. Bazarov et al., Appl. Phys. Lett. **98**, 224101 (2011).

[8] L. Cultrera et al., Appl. Phys. Lett. **99**, 152110 (2011).

[9] I. Bazarov et al., J. Appl. Phys. **103**, 054901 (2008).

[10] S.B. van der Geer and M.J. de Loos, *General Particle Tracer User Manual* `www.pulsar.nl`

[11] Advanced Photon Source Upgrade Project Preliminary Design Report `http://www.aps.anl.gov/Upgrade/`

[12] I. V. Bazarov et al., Phys. Rev. ST-AB 14, 072001 (2011).

[13] N. Valles et al., Proceedings of IPAC 2012, WEPPC075

[14] N. Valles et al., WEPWO068, these proceedings.

[15] N. Valles et al., WEPWO069, these proceedings.

[16] R. Eichhorn et al., WEPWO059 these proceedings.