The past year has been one of considerable progress on a great many different fronts of the ERL project. On Valentine’s Day, we received notification of an award from the National Science Foundation for our Phase 1a ERL Project. The award, $18 million over four years, supports the development of the high beam brightness, high average current electron injector for the ERL. The brilliance, current and temporal characteristics of the ERL are determined, first and foremost, by the injector. The injector will deliver a 5 to 15 MeV, 100 mA average current, very low emittance beam in a continuous train of short duration bunches at 1300 MHz, performance parameters well beyond anything yet demonstrated.

Long before the NSF award, Cornell University advanced funds to allow initial development of the photoemission electron gun that is central to the injector, and to proceed with several expensive, long lead time procurements. With this support, contracts have been let for the high power 1300 MHz klystron that will deliver RF power to the superconducting cavities of the injector, for the 750 kV, 100 mA high voltage power supply for the electron gun, and for the large ceramic insulator that will isolate the cathode structure of the gun. Each of these procurements is for technically unique equipment with exceptional characteristics. The klystron, for example, has seven cavities to provide a large gain-bandwidth product and very high efficiency at high average power. The design review for this tube will be in late June, and the first article is expected at Cornell before the end of the year.

Fifteen hundred square feet of laboratory space in Wilson Lab has been made available for the development and construction of the photoemission electron gun and its associated laser. The lab includes clean space for activities such as polishing the electrode structures of the gun and assembling the gun ultrahigh vacuum chambers, as well as for experiments on photocathode preparation, field emission reduction, and outgassing measurements. With the addition of a beam dump and radiation shielding, we anticipate operating the complete electron gun at 100 mA average current in this room.

Development of the electron gun is well underway. The designs for the gun chamber, its vacuum system, and the electrode structures have explicitly addressed problems such as photocathode operating lifetime, photocathode cooling during high current operation, and high voltage breakdown across the cathode-anode gap and along the surface of the ceramic insulator. The gun vacuum chamber is being fabricated, with delivery expected in late June. The non-evaporable getter (NEG) pumps and ion vacuum pumps for the gun chamber are in hand, and the large ceramic insulator is expected by late August. We hope to deliver the first electrons from this gun before the end of the year.

A schematic picture of the entire electron injector is shown in Fig 1. A superconducting RF (SRF) accelerator will follow the electron gun, to raise the final injector beam energy to 5 to 15 MeV.

Fig 1: A schematic picture of the entire electron injector. A DC photoemission electron gun on the left delivers a 100 mA average current beam. The beam passes through two solenoid lenses and a normal conducting buncher cavity and enters the injector cryomodule, containing five two-cell superconducting cavities. Following the cryomodule, quadrupole lenses focus the beam, and dipoles merge the beam onto the axis of the main ERL linear accelerator.
This will be the first SRF accelerator to operate with a 100 mA average current beam. It will have five two-cell SRF accelerator cavities, and deliver 500 kW of power to the beam, limited by the installed RF power. The design for the two-cell cavities of this small accelerator is mature, and has been checked in detail by measurements on three full size copper models. These copper models show that the fundamental resonant frequency is correct, and that the lowest frequency higher order modes (HOMs) propagate out of the cavity to the HOM loads. The first niobium cavity is now in fabrication, and will be tested for its SRF characteristics before the end of the year. The final qualification of the cavity design will be a test of a cavity assembled in its liquid helium vessel, with its frequency tuner and RF power couplers attached.

Each SRF injector cavity will have two nominally identical RF power couplers that deliver the microwave power. The idea of using a pair of opposed couplers is both to reduce the power delivered per coupler, and to eliminate, to first order, the transverse kick to the beam that would come from a single coupler. To allow the beam energy to be varied while keeping the beam load matched to the RF power source requires a variable coupler. A detailed design for this coupler has been completed, and proposals for the construction of the first two couplers have just been received from several bidders. We anticipate testing the first coupler pair early next year, with award of the order for the remaining couplers to follow shortly thereafter.

The high average current, short bunch duration beam of the ERL generates very high HOM power up to very high frequencies in the cavities. This power must be removed to avoid beam quality degradation and excessive heat load at the cryogenic operating temperature of the SRF cavities. HOM damping at frequencies up to about 40 GHz is required. No single known material has sufficient RF absorption over this broad frequency range. We have studied a large number of candidate RF power absorbing materials as a function of frequency at low temperature, and have identified a combination of three materials that will, working together, provide good HOM damping to the required 40 GHz. Construction of the first HOM loads for the injector from these three materials is underway.

The five SRF injector cavities with their liquid helium vessels and frequency tuners attached, along with their power couplers and HOM loads, will be assembled in a single cryostat, called a cryomodule. The design for this cryomodule has been adapted from the design for the TESLA cryomodule. Our initial design was reviewed by outside experts last summer, and has been revised significantly since that time. The final design will be again reviewed prior to the start of construction. Fig 2 shows a two cavity segment of the present cryomodule design.

**Fig 2:** A view of a two SRF cavity section of the Injector Cryomodule. All elements are supported from the large diameter pipe that transports 2 K helium gas back to the refrigerator. The SRF cavities are inside their liquid helium vessels, which in turn are inside multi-bladed frequency tuners. The cold portion of two RF power couplers is seen. The HOM loads are mounted in the red brackets.
We have conducted two very important experiments in collaboration with Jefferson Laboratory (JLab) this year. Each of these experiments has favorably answered key questions important to the full scale ERL X-ray source. In the first of these, a new digital RF control system developed at Cornell was tested on superconducting cavities in two accelerators at JLab. In one test, the control system held the cavity field constant at the level of $10^{-4}$ in amplitude and 0.02º in RF phase with 5.5 mA of beam circulating in the energy recovery mode. At this level, the beam was extracting from and returning to the cavity 47 kW of average power, while being controlled with only 200 W of RF power from the klystron – powerfully demonstrating the utility of energy recovery. In a second test, the control system successfully ramped the field in a cavity from zero to high accelerating gradient in well under a second. During this ramp, the 1.3 GHz cavity resonant frequency was tracked and held fixed by the control system, though the Lorentz detuning was over 150 Hz and the cavity bandwidth only 6 Hz. The performance of the new control system is completely adequate for an ERL such as we plan for construction at Cornell.

A second experiment was conducted on the accelerator of the JLab free-electron laser (FEL), to study the recirculating beam breakup (BBU) instability. In BBU, the beam completes a positive feedback loop in which the beam is kicked by a deflecting higher order mode in a particular cavity and, above some threshold current, feeds enough energy back into that same mode on its second pass through the cavity that the deflection of subsequent beam is increased. It is important to have a good quantitative understanding of BBU, as it limits the maximum current that can be circulated in an ERL. Cornell and JLab accelerator physicists made an extensive series of measurements of BBU at the FEL as the accelerator optics and HOM damping were varied. In general, good quantitative agreement was obtained between the calculated and measured BBU threshold current, validating the codes used to predict this current. Further experiments are planned. The codes predict a BBU threshold current well above 100 mA for the Cornell ERL.

Operation of the photoemission electron gun requires a high average power laser delivering a 1300 MHz train of short (10 to 40 ps) optical pulses, precisely synchronized with a Master Oscillator that sets the phase of the microwave fields in all SRF cavities. The initial laser will be an oscillator-amplifier configuration operating in the near IR, and frequency doubled into the green. We have a strong collaboration with the group of Prof. Frank Wise in the Cornell Applied and Engineering Physics Department, and a graduate student working on the laser design. In addition, we recently hired Dr. Dimitre Ouzounov to lead the laser work for the ERL.

There is no way to analytically calculate the optimal focusing conditions, field strengths, and element locations in the full injector. The addition of other constraints, such as developing a design that can be physically assembled, leaving room for vacuum valves, and adding the distance necessary to transition from room temperature to the 2 K temperature of the SRF cavities, only complicates the problem. These realities led us to conduct a computational optimization, using massive parallel processing, of our original injector design. This optimization has led to simulated values for the electron beam transverse emittance considerably smaller than those of the original design, leading to optimism that we will be able to deliver a much higher beam brightness than in our original proposal, with a corresponding improvement in the X-ray beam brightness and coherence.

With other laboratories, Cornell sponsored a very well attended ICFA (Internat, Committee for Future Accelerators) Workshop on ERL Injectors at Jefferson Laboratory in March. Over 150 participants from Asia, Europe, and the US attended. The workshop had four working groups, covering the topics of Photoemission Electron Sources, RF and SRF issues, Beam Dynamics, and Beam Diagnostics. Many good ideas were discussed, and there were a number of joint sessions between various working groups. Another workshop is planned in two years at Daresbury.

Demonstration of a successful injector is but one of many technical challenges of an ERL X-ray source. The ERL will be the first continuous duty hard X-ray source that is essentially fully transversely coherent. It will also deliver X-ray pulses orders of magnitude shorter in time than storage rings. Effective utilization of these properties will require advances in the state-of-the-art in machine stability, X-ray optics, detectors, and experimental techniques. The CHESS philosophy is to develop these technologies by application to specific experiments, in order to keep the development focused and coupled to community needs. Accordingly, we plan to have a series of international workshops over the next 18 months to explore specific scientific areas and to define the beamline and experimental needs.

We would welcome your input and participation in the workshops. The workshop topics, and the lead CHESS organizers, are given below. Please contact the organizers with your ideas and suggestions, or if you wish to participate in the workshops:

- Sub-picosecond science (Joel Brock)
- Nanometer beams (Don Bilderback)
- Coherent imaging (Ernie Fontes)
- Biological applications (Richard Gilillan)
- High-pressure science (Neil Ashcroft)
- Nanoscience & soft-matter (Detlef Smilgies)