

ERL07 WORKING GROUP 1 SUMMARY: ELECTRON GUNS AND INJECTOR DESIGNS*

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Abstract

This paper summarizes the presentations and discussions of Working Group 1 - Electron Guns and Injectors – of the 2007 Energy Recovering Linacs Workshop (ERL07). There was general consensus that there has been considerable progress in the areas of guns, photocathodes, drive-laser development and injector design since the previous workshop ERL05 [1]. Many of these developments are described below.

INTRODUCTION

The ERL07 workshop extended over three days with five half-day sessions devoted to formal presentations and roundtable discussions. Working Group 1 (WG1) sessions were well attended, with 22 talks and joint sessions with Working Groups 2 and 3 (Optics and SRF, respectively).

The WG1 charge was similar to that of the previous workshop, with “Injector” defined as the part of the accelerator up to and including the merge with the returning high-energy beam. The charge assumes that guns must provide reliable CW beam with average current ~ 100mA and emittance of a few microns (normalized RMS). This provides the basis for photocathode and laser power requirements. Other specific charge items are listed in the appendix.

The success of the workshop toward meeting the charge likely depends on each attendee’s perspective. Admittedly, little attention was devoted to discussion related to the merge, at least in WG1. And because many facilities are still busy designing/constructing guns, lasers systems and beamlines, not all speakers were in a position to discuss actual beam-based experimental studies. Clearly, beam-based discussions will receive more attention at future workshops, as the global ERL effort continues to mature. Highlights of developments related to guns, drive lasers and photocathodes are described below. Highlights related to injector optics and simulations are included in the WG2 summary.

GUN TECHNOLOGY

Considerable progress was noted in the field of gun development with substantial research and development devoted to each technology: DC high voltage, normal and superconducting RF and novel designs.

DC High Voltage Photoguns

In 2005, only one DC high voltage gun with bias voltage > 250kV was providing beam for an ERL

program. Today, there are five DC high voltage guns in operation or soon to be operating: two guns at the JLab FEL, one gun at Daresbury ERLP, one gun at Cornell University and one gun at RIKEN/JAEA.

The photogun at the JLab FEL continues to hold records for highest operating bias voltage (350kV) and the highest prolonged operating current (8mA). The GaAs photocathode within the JLab/FEL gun has been used for 36 months, with over 900 hours in CW mode delivering 7000 Coulombs at average CW beam current between 1 and 8 mA and 135pC bunchcharge. During this period, the photocathode was activated a total of 9 times with an average of 6 re-cesiations per activation, evidence of the gun’s long term sustainability to support an ambitious scientific program. The JLab FEL team has been very pleased with gun performance, as demonstrated by a number of ERL/FEL milestones including 250pC bunchcharge operation at 3mA average current and sustained FEL output power of 14kW at 1.6 μ m wavelength. Some of the gun technological issues to be addressed in the near future include: operation at higher bias voltage and higher bunch charge, and reduction of beam halo that likely originates from the long electron bunch tail.

The JLab FEL team has recently begun constructing a second DC high voltage photogun to be used at a dedicated test stand with the immediate goal of demonstrating 1nC operation to support their 100mA ERL endeavors. The test stand will provide opportunities to address numerous technological challenges (without interrupting FEL operations) including field emission suppression via electrode coatings, improved vacuum via outgassing reduction and NEG coating of vacuum chamber surfaces, and installation of a semi-load lock to speed replacement of photocathode samples without venting the HV chamber of the gun.

The ERLP photogun at Daresbury Laboratory is a copy of the Jefferson Laboratory IR-FEL gun. In the last year, it delivered beam at both 250 and 350 kV, and has withstood high voltage conditioning to 485 kV. The gun and drive-laser system have met the design specifications of delivering 100 μ s macrobunches at up to 20 Hz repetition rate, though the maximum measured bunch charge of 22 pC falls short of the 80 pC specification. Extensive beam halo was identified as a problem, and work to understand the cause is progressing. Difficulties were encountered during the activation of the GaAs

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photocathode to negative electron affinity: the photocurrent swamped by a much larger non-constant background originating from ionized cesium from the cesium channel dispensers. Quantum efficiencies of $\sim 1.5\%$ have been attained in the gun (the minimum design specification being 1%), with QE up to 3.5% attained in an off-line test chamber. Photocathode lifetime has been extremely poor, largely due to vacuum issues in the gun chamber. Improvements in wafer handling and gun bakeout procedures promise to yield higher QE with better lifetime during the next phase of gun commissioning, however, a series of leaks have hampered progress. Two consecutive leaks on a spacer flange prompted the welding of one side of this spacer directly to the gun chamber, followed by a further leak through a braze joint on the main ceramic which necessitated its replacement with the spare ceramic insulator. The gun vacuum chamber is currently baking. It is hoped that commissioning and optimization of the gun can be completed before the end of 2007, achieving all design parameters and taking emittance measurements over a range of bunch charges. Once this is achieved, the diagnostics beamline will be removed and the booster linac module connected in its place. Energy recovery is planned for the first quarter of 2008.

The DC high voltage gun program at Cornell University has made great progress since ERL05, with demonstrated operation of their gun at 250kV and 5 mA average current. Higher voltage was briefly obtained (330kV) however excessive field emission and insufficient bleed resistivity along the inner surface of the insulating ceramic resulted in a vacuum punchthrough. This ceramic was repaired and the gun continues to be used for emittance, lifetime and drive laser studies while awaiting delivery of a new ceramic insulator. B. Dunham reported unmistakable evidence of improved electrode performance via application of the SRF-cavity cleaning technique referred to as high pressure rinsing. Large area test electrodes that were subjected to high pressure rinsing could be operated at significantly higher field gradients (>30 MV/m) compared to electrodes that were hand-polished with diamond-paste, the traditional preparation technique. Presumably, high pressure rinsing efficiently removes particulate matter that becomes embedded in the electrode surface during machining and polishing, resulting in a smoother surface capable of achieving higher field gradients without field emission. Besides gun development, the Cornell group has constructed an impressive diagnostic beamline and high power dump and will soon install the SRF accelerating cavities to accelerate high average current beam to 15 MeV. An innovative green-light fiber-based drive laser is described below.

Significant progress was reported by the RIKEN/JAEA group toward developing a 250kV and 50mA DC high voltage GaAs photogun for the ERL light source in Japan. A side-ceramic style gun has been constructed, with planned beam delivery during the summer of 2007. Results from a separate vacuum test chamber suggest

AlGaAs provides higher QE and improved lifetime compared to bulk GaAs.

Normal Conducting RF (NCRF)

NCRF guns provide low duty factor pulsed beam at numerous facilities worldwide including FLASH, PITZ, BNL, LANL, CLIC/CTF, KEK and PAL. Although none of these guns can be used to provide CW beam at 100mA average current, their experiences at high bunch charge, technological developments and lessons-learned can be useful for the ERL community.

The NCRF photogun program at FLASH/DESY was described in two talks by J.-H. Han. The first talk focused on operating experience of the FLASH injector, which has been very successful and contributes significantly to the overall success of the FLASH User program. The FLASH NCRF gun is a 1.5 cell copper cavity resonant at 1.3GHz with operating gradient of 44 MV/m at the Cs₂Te photocathode. Projected normalized 90% rms emittance is ~ 1.6 mm mrad at 1 nC bunch charge, consistent with expectations. Two problems were described: unexplained photocathode damage and excessive dark current that contributes to beam halo which can activate/damage beamline components. Photocathode damage is under investigation while dark current was successfully decreased by moving the gun further from the first accelerating structure, to provide space for an aperture "kicker". J.-H. Han's second talk described simulations that suggest it will be possible to further decrease dark current by adjusting the length of the gun half-cell, to separate (in RF phase) dark current from photocurrent.

S. Lidia described a novel NCRF gun design that would operate in the VHF range, between 65 and 200 MHz, in a sense combining the best features of NCRF and DC high voltage designs. Such a gun could conceivably operate at high average current in CW mode because the RF power density at the cavity walls would be lower, thereby reducing the complexity of thermal management. The large gun geometry provides opportunity for improved vacuum pumping, suggesting the possibility of using vacuum-sensitive photocathodes such as GaAs. Extensive simulations were presented and Lidia hopes for funding approval to support gun construction.

Regrettably, the 100mA LANL/AES NCRF gun program was not represented at the workshop.

Superconducting RF (SRF)

There are healthy SRF gun programs at Rossendorf and BNL. J. Teichert began his description of the Rossendorf effort by stating the overarching motivation for pursuing SRF gun technology, namely it promises low emittance and high beam energy in a short distance like an NCRF gun but without thermal problems associated with inefficient conversion of RF energy to beam energy, and should therefore allow production of very high average current beam. He listed the major technological challenges of SRF guns: a) cavity contamination and Q-degradation due to sputtering of particulates from the

Table 1 Gun technology candidates for 100 mA ERLs

Gun	Pros	Cons	Challenges	Demonstrated Performance
DC	<ul style="list-style-type: none"> • Considerable experience: 5 guns exist, however none above 350kV • Demonstrated high QE • Likely the cheapest technology 	<ul style="list-style-type: none"> • Need buncher and additional accelerating cavities • Field emission catastrophic • UHV/XHV required 	<ul style="list-style-type: none"> • Vacuum, • Field emission • HV breakdown • Cathode lifetime due to imperfect vacuum and ion bombardment • Eliminating tail on electron bunch • Cathode cooling at high laser power 	<ul style="list-style-type: none"> • ERL at 8mA, 135pC, 10um • Recent demo 270pc at 3mA
NCRF	<ul style="list-style-type: none"> • High beam energy in short distance • Prompt emission • No cryo issues 	<ul style="list-style-type: none"> • RF power mostly heats the gun chamber. • Vacuum degrades due to thermal heating • Lots of cooling required • Complex fabrication 	<ul style="list-style-type: none"> • Providing adequate vacuum pumping • Thermal management • Complicated brazing 	<ul style="list-style-type: none"> • 130mA peak at 25% duty factor (40mA ave), 5um at 1 nC
SRF	<ul style="list-style-type: none"> • High beam energy in short distance • Efficient transfer of energy from RF to beam. • Prompt emission • Excellent vacuum 	<ul style="list-style-type: none"> • Keeping gun clean, free of particulate contamination • Complicated overall design 	<ul style="list-style-type: none"> • Cathode exchange and cleanliness • Managing thermal load due to photocathode 	<ul style="list-style-type: none"> • 100uA ave, 2 um at 10 pC

photocathode during gun operation and from debris generated during photocathode installation and removal, b) problems associated with operation of the photocathode at cryogenic temperature, c) problems associated with the photocathode and/or photocathode holder adversely affecting the performance of the superconducting cavity, and d) emittance compensation cannot be accomplished as easily as for NCRF guns. He then went on to describe the many steps Rossendorf has taken to overcome these technological challenges with detailed descriptions of the photocathode mount and cooling system, Cs₂Te photocathode preparation and transport systems, and the gun ½ cell design with “retreated” (i.e. choke joint) photocathode geometry. The SRF gun mounts directly to a 3-cell TESLA-design SRF cavity, housed in the same cryomodule. Progress has been good with expected operation at 1mA average current at the ELBE linac during summer 2007.

BNL is pursuing two SRF gun programs, one at high average current (up to 500mA) and another at more modest current of 1mA. A. Burrill described the BNL/AES high current SRF gun program: a 703 MHz ½

cell gun with two high-power RF coaxial input couplers (1 MW total) and a choke-joint design to accommodate the CsK₂Sb photocathode. Some aspects of the gun are still in the design phase, but extensive tests with ½-cell 1.3 GHz cavities are in progress to support choke joint studies. BNL infrastructure continues to grow (facilities, photocathode preparation chambers, drive laser) with ERL commissioning expected in 2009.

J. Smedely of BNL described a program to investigate the possibility of producing 1 mA average beam current using a compact and simple SRF gun, where “simple” refers to the idea of using the niobium surface of the cavity itself as the photoemitter, or a thin layer of another superconductor (e.g., lead) applied to the cavity. Such a gun would not require a vacuum apparatus to replace photocathodes, and it would greatly reduce the complexity of the cryostat. To investigate this possibility, he used the JLab ½-cell “plug” gun to measure QE of niobium and lead at cryogenic temperature. Niobium was found to have poor QE, insufficient for 1mA beam generation with today’s lasers whereas lead appears to be a promising candidate material and it does not severely adversely affect cavity performance.

LASERS

Regardless of gun technology, the 100mA ERL-design requirement places a large burden on the drive laser system. Assuming a photocathode with 10% QE (perhaps a non-trivial assumption), it takes 2.3W to generate 100mA. Of course more power is required to compensate for optical losses on the laser table and inevitable photocathode QE decay that occurs during beam delivery. Furthermore, the laser must possess RF structure to accommodate synchronous photoinjection and some ERL designs require very high pulse repetition rates (> 1 GHz) not readily commercially available. This loose scenario sets the minimum drive laser power requirement for the 100mA ERL between 10 and 25W. At ERL05, this represented a significant R&D challenge of its own. Fortunately, to ERL07 attendees' great satisfaction, this requirement does not seem so formidable, thanks to fiber amplifier technology that can support operation at 532 nm and 780 nm via frequency doubling from 1064 and 1560 nm, respectively (common telecommunications wavelengths) and powerful commercial Nd:host laser systems that produce very high power green light and even tens of Watts in the ultraviolet, which opens up possibilities for using Cs₂Te photocathodes (more below).

Two fiber-based laser systems were described: one constructed at Cornell University and one at CEBAF/Jefferson Lab. Both systems are master-oscillator/power-amplifier (MOPA) designs. Diode seed lasers are used to create the required RF time structure and fiber amplifiers are used to boost the average power to multi-Watt levels. The light from the fiber amplifier must then be frequency doubled to produce useful visible or near-infrared light, a process that can be very efficient (as high as ~ 50%). The Cornell design uses a short pulse (~ 2ps) modelocked fiber-coupled diode seed laser and a clever optical delay line technique to create "flat top" pulses with discretely variable pulsewidth. The CEBAF design relies on the technique "gain switching" to create a reliable and phase-stable optical pulse train. To date, Cornell has produced 4W average power at 532 nm and 1300 MHz, with 20ps flattop pulses. The CEBAF system provides 2W average power at 780nm and 500 MHz, with 35 ps Gaussian pulses. Based on numerous journal publications [2], it's reasonable to assume that the power of fiber-based laser systems can be scaled using existing fiber amplifier technology.

As for Nd:host laser systems, the JLab/FEL recently replaced their ~ 5W commercial modelocked Nd:YLF laser with a MOPA-based system composed of a commercial passively-modelocked Nd:YVO₄ master oscillator and four daisy-chained double-pass Nd:YAG amplifiers. Useful light at 532 nm is obtained via frequency doubling using LBO. The system can operate at two pulse repetition rates, providing more than 25W at 75 MHz and 13W at 750MHz. Laser table measurements indicate good mode quality, pulsewidth, timing jitter and phase noise values. This new drive laser was installed at the drive laser clean room and commissioning will begin

when the JLab FEL resumes beam operations following a scheduled summer 2007 shutdown.

T. Rao described a very promising new commercial Nd:YVO₄ laser system from Lumara Laser GmbH: a passively modelocked, coupled-cavity MOPA design that produced 87W average output power at 532 nm and 35W at 355 nm, at 110 MHz pulse repetition rate with 33 ps pulses [3], and good spatial mode quality. Based on these published results and conversations with the vendor, BNL placed an order for a similar laser system. The availability of high power (> 10W) at UV wavelengths opens up the possibility of using Cs₂Te photocathodes for 100mA ERLs and represents a modest contradiction to a statement by I. Will during his talk on the opening day of the workshop, namely, that it will be difficult to obtain more than one Watt average power at UV wavelengths.

Synchronization of the drive laser optical pulse train to the accelerator RF remains an important issue as stated by G. Hirst during his plenary talk and reiterated by L. Jones during his WG1 talk describing the drive laser for the ERLP at Daresbury Lab. The commercial modelocked Nd:YVO₄-based system from High Q meets the ERLP timing stabilization requirement (< 1ps), although commissioning studies illustrated the importance of reliable infrastructure (e.g., laser room temperature control, water cooling), minimizing laser table vibrations, frustrations associated with being hostage to one vendor and/or obsolete equipment, and the need for adequate and simple computer control. M. Poelker suggested the optical pulse forming technique gain-switching as an attractive alternative to modelocking. Gain-switching is a purely electrical technique that does not depend on laser cavity length, and consequently does not require active feedback control for timing synchronization/stabilization. Unfortunately, gain switching does not provide a means for easily changing pulsewidth or pulse shape, and therefore may not lend itself to temporal pulse shaping.

Two speakers discussed experimental results relating progress toward spatial and temporal laser beam/pulse shaping. The Cornell group plans to drive their gun with "beer can"-shaped optical pulses. B. Dunham described using a commercial refractive beam shaper from Newport Corporation that converts a Gaussian input beam into a top-hat profile. The beam shaper is simple to use and relatively inexpensive (~5k\$) although the input beam conditions (collimation and beam diameter) must be strictly met to achieve good results. For temporal pulse shaping, they have implemented a pulse stacking scheme first described in a paper from 1979 [4]. A birefringent crystal is used to split an input pulse into two pulses separated in time (and with orthogonal polarization). The time delay between pulses is determined by the crystal length. For their input pulse of 2.5 ps, and using four birefringent crystals, Cornell obtained 20 ps nearly flat top pulses with fast rise and fall times (~ 1ps).

D. Garzella of CEA/Saclay described successful top-hat spatial profile generation using aspheric lens combinations, with lens dimensions determined using the computer program ZEMAX. He also described plans for

constructing a deformable mirror to generate other spatial profiles. As for time domain pulse shaping, CEA/Saclay has created flat-top, parabolic and ellipsoidal pulseshapes using a commercial product called DAZZLER, from Fastlite, which describes their product as an acousto-optic programmable dispersive filter (AOPDF) that is compact, extremely fast and completely turn-key.

PHOTOCATHODES

As noted at the previous ERL workshop [5], there are two obvious photocathode choices for 100mA ERLs, GaAs and multi-alkali antimonide, where the words “obvious choice” relate to the availability of high average power green-light drive lasers. If, as noted above, powerful lasers become available at UV wavelengths, Cs₂Te also becomes a reasonable photocathode choice. Advantages and disadvantages of these photocathodes are listed in Table 2. In short, GaAs-based photocathodes promise high QE (>10%) and low thermal emittance but thick samples produce long electron bunch tails which can be especially problematic in managing halo. GaAs photocathodes also require exceptionally good vacuum to provide a long photogun operating lifetime. Multi-alkali antimonide photocathodes such as CsK₂Sb promise high QE and fast response time without tails however their positive-electron affinity (PEA) nature results in larger beam emittance. Most workshop attendees believe CsK₂Sb photocathodes are more “rugged” compared to GaAs photocathodes, and will provide longer operational lifetime under comparatively worse vacuum conditions. The PEA photocathode Cs₂Te has similar advantages and disadvantages as multi-alkali antimonide photocathodes, but as mentioned above, will require powerful UV drive lasers.

Table 2 High QE Photocathode Summary

	GaAs	CsK ₂ Sb	Cs ₂ Te
Pros	<ul style="list-style-type: none"> Green and near-IR light Lower thermal emittance 	<ul style="list-style-type: none"> Green Light Rugged, can survive worse vacuum Short pulse, no tail 	<ul style="list-style-type: none"> Rugged, can survive worse vacuum Short pulse, no tail
Cons	<ul style="list-style-type: none"> long tail Requires UHV/XHV 	<ul style="list-style-type: none"> Higher thermal emittance 	<ul style="list-style-type: none"> Higher thermal emittance Requires UV light

Besides these “standard” photocathodes, T. Rao of BNL reported continued progress toward developing a diamond secondary-emitter photocathode, where photoemission from “standard” photocathode material is amplified using a secondary-emitter diamond layer. For

the first time, BNL reports amplification of beam in “photoemission mode”, i.e., conditions similar to those encountered in an RF gun.

CONCLUSION

The authors of this summary believe there was general consensus that considerable progress has been made since ERL05, particularly in the areas of guns, drive laser development and toward implementing new modeling tools for gun and injector design. Still, considerable technological challenges remain, as illustrated by considering that at 100 mA, the photogun must deliver 360 Coulombs per hour or 8640 Coulombs per day. A photocathode with 10% QE requires over 2W initial laser power. If the photogun provides 1000 Coulombs before photocathode QE drops to 1/e of its initial value, the required drive laser power will be 100W in just 10.5 hours, at which point it is time to move the laser beam to a fresh photocathode location (downtime ~ 10 minutes), time to swap the photocathode (1 hour), or time to heat/reactivate photocathode (8 hours). To date, the most powerful operational drive laser provides 25 W and the best reported photogun charge lifetime (at milliampere beam current) is 500 Coulombs (JLab/FEL). So clearly, the ERL community has considerable challenges to overcome. Fortunately, there appears to be considerable worldwide enthusiasm for tackling these challenges.

APPENDIX: WG1 CHARGE

Gun Technology (DC high voltage, normal conducting RF, superconducting RF, and hybrid designs):

- Obtain status reports from each gun program
- Update the gun table. List advantages, disadvantages, state-of-the-art, milestones since ERL05, expected required level of continued R&D
- Discuss technological challenges: vacuum, field emission, load locked designs, photocathode cooling, HV breakdown, beam management, photocathode QE degradation, cathode adverse effects on RF cavity, etc.,

Photocathodes and Lasers:

- Update the photocathode table. List pros/cons of each photocathode material, identify the appropriate laser wavelength, infrared versus green versus ultraviolet, measured QE, necessary laser power for 100mA beam, response time
- List drive laser candidates for each photocathode: max available power, approx. cost and complexity, pulse forming mechanism, pulsewidth.

Beam dynamics and emittance preservation techniques:

- Laser pulse shaping techniques
- bunch compression techniques
- RF focusing
- Graded beta cavities
- Identify the biggest challenges

Injector designs and benchmarking codes:

- List the computational methods used for each major design effort
- List advantages and disadvantages of each code (superfish, parmela, astra, track, egun, microwave studio, mafia, etc.,). How many versions of each code exist?
- Status of efforts to benchmark codes against beam-based measurements

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