Available online at www.sciencedirect.com

SCIENCE DIRECT®

Nuclear Instruments and Methods in Physics Research A 557 (2006) 337–344

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

www.elsevier.com/locate/nima

Summary, Working Group 1: Electron guns and injector designs

I. Ben-Zvi[a,*], I.V. Bazarov[b]

[a]*Brookhaven National Laboratory, Upton, NY 11973, USA*
[b]*Cornell University, Ithaca, NY 14853, USA*

Abstract

We summarize the proceedings of Working Group 1 of the 2005 Energy Recovery Linac (ERL) Workshop. The subject of this working group, the electron gun and injector design, is arguably the most critical part of the ERL as it determines the ultimate performance of this type of accelerators. Working Group 1 dealt with a variety of subjects: The technology of DC, normal-conducting RF and superconducting RF guns; beam dynamics in the gun and injector; the cathode and laser package; modeling and computational issues; magnetized beams and polarization. A short overview of these issues covered in the Working Group is presented in this paper.

PACS: 41.75.Ht

Keywords: Energy recovery linac; High average current; Superconducting RF; Photoinjector design; Ampere class; Photocathode

1. Introduction

This paper is the summary of the proceedings of Working Group 1 of the 2005 Energy Recovery Linac (ERL) Workshop, dealing with the electron gun and injector issues. We define Injector as a part of the ERL up to (and including) the merge with the returning high-energy beam. Electron average currents of 100 mA or more are envisioned, with a good emittance of sub micron (normalized RMS) at the lower current to a few microns at the higher current. Certain applications will require magnetized electron beams or very high charge, lower repetition rate bunches, in which case the emittance can go up another order of magnitude.

The subject of this working group, the electron gun and injector design, is arguably the most critical part of the ERL. It is here that the ultimate performance of the ERL is determined: What will be its current, its bunch structure, and its transverse and longitudinal emittances. These parameters can only be degraded in subsequent parts of the ERL, never improved. The gun and injector are also the most dynamic elements, with rapid progress being made. It has some of the most intractable problems, in particular the issue of providing a good photocathode and dealing with severe space–charge interaction and limited space. The flip side of this is that any improvement made in this relatively small element affects the performance of the complete ERL and can easily lead to dramatic improvements. Working Group 1 dealt with a variety of subjects: The technology of DC, normal-conducting RF and superconducting RF guns; beam dynamics in the gun and injector; the cathode and laser package; modeling and computational issues; magnetized beams and polarization.

By necessity the gun and injector sit on the confluence of a number of technologies and disciplines, such as lasers, photocathodes, high RF power (the gun and injector are not energy recovered), high-field cavities operating CW, particularly complex beam dynamics due to strong space–charge interactions, particularly difficult diagnostics due to the low energy, high current and limited space, and so on. Due to the connection to other disciplines represented in the workshop, we held two joint sessions with other working groups, to address the following:

- Merger design and limiting phenomena with Working Group 2.

---

[*] Corresponding author. Tel.: +1 631 344 5143.
E-mail address: ilan@bnl.gov (I. Ben-Zvi).

0168-9002/$ - see front matter © 2005 Published by Elsevier B.V.
doi:10.1016/j.nima.2005.10.097

- Necessary beam diagnostics in the injector with Working Group 4.

The summary of these subjects will be covered in the summary of these other working groups. What became apparent in the discussion is that the advent of the zigzag merger leads to a significant brightness improvement in the moderate and high bunch-charge beams. As far as diagnostics are concerned, key injector diagnostic requirements are that most diagnostics must work at low energy (<10 MeV); a need to make the injector as short as possible (and that implies compact diagnostics); and that all diagnostics should be designed for low impedance with CW capability desired at full charge and full repetition rate.

In the following we will provide the material grouped by the working group main subjects. In addition to this summary, various members of the working group were encouraged to summarize specific subjects, and these summaries are presented as independent papers in these proceedings. These papers include the following:

Photocathodes, T. Rao et al.
Lasers, M. Shinn et al.
SRF Guns, A. Burrill et al.
DC Guns, C. Sinclair et al.
Normal-conducting RF guns, D. Dowell et al.

In summary, Working Group 1 had a most active program and enjoyed the largest number of participants, arguably indicative of either the significance of the subject of RF/DC/SRF guns and injectors, or the large number of open problems and room for innovations in this subject. More than half of the total of 18.5 h the group spent together was devoted to lively discussions. Of the rest, invited talks outnumbered contributed talks by a ratio of about 3:1.

2. DC, normal-conducting RF and superconducting RF guns

The subject covered in the working group was also addressed in the plenary session by Alan Todd (Advanced Energy Systems), who covered “Electron Guns and Injector Designs”. AES is involved in a number of electron guns, from the DC gun and its injector system with Jefferson Laboratory, through the normal conducting RF gun with Los Alamos National Laboratory to the superconducting RF gun with Brookhaven National Laboratory. Todd surveyed 11 different guns serving in various ERLs, including operating guns such as DC/thermionic emission (JAERI FEL, BINP FEL) and DC/photocathode (JLab FEL); the normal-conducting retired RF gun (Boeing R&D accelerator), which is still state-of-the-art; other RF guns under construction, the LANL/AES normal conducting, the BNL/AES superconducting gun for the R&D ERL, some RF guns under analysis (LUX at LBNL, 4GLS at Daresbury) and DC guns under construction (AES/JLab injector test stand, Cornell injector test stand, Daresbury ERLP). The survey includes over 20 parameters, status information and comments,—an extensive survey. He includes a list of “requirements”, which are broadly defined with a goal and range of parameters to be found: Output energy ~7 MeV (2–15); CW average current ~200 mA (100–500); transverse emittance $<6\,\mu$m RMS normalized (0.1–6); longitudinal emittance <145 keV-ps RMS (25–145); bunch length ~4 ps (2–7); energy spread $<0.5\%$ (0.1–0.5) at 7 MeV; RF frequency ~700 MHz (500–1300); 500 kW RF feedthroughs (50–500).

Following that, Todd provides an appraisal of the issues facing the various guns being pursued in the community:

DC guns with SRF boosters

- Maximum achievable gradient and voltage (~7 MV/m and ~500 kV) w.r.t. field emission and breakdown.
- Maximum achievable bunch charge (~1 nC) w.r.t. performance requirements due to reduced initial accelerating gradient and space charge effects.
- Ion backbombardment and GaAs (or other) cathode performance/lifetime.
- That said: relatively mature technology that will likely deliver 100+ mA injectors.

NC RF guns

- Maximum achievable gradient (~10 MV/m) w.r.t. thermal stress limits.
- Efficiency penalty and cost due to impedance and ohmic losses.
- Achievable vacuum conditions and visible cathode selection (multi-alkali?)/performance/lifetime.
- That said: uncertain path forward largely because of cathode issues but still the state-of-the-art.

SRF guns

- Maximum achievable gradient (~20 MV/m) w.r.t. peak gun fields.
- Viable choke joint design and cathode compatibility with SRF environment and contamination.
- Cathode selection/performance/lifetime but excellent vacuum properties.
- Least mature but most desirable option delivering RF gun performance with DC gun efficiency.

All technologies

- Dark current limit
- RF power delivery
- HOM, wakefield and BBU issues at high beam power
- CSR in compression sections.

Todd concludes the survey of the three technology options with the observation that we must demonstrate practical, compatible cathode and drive laser options for each injector type, we must pay attention to HOM and CSR issues in injectors and we must successfully demonstrate high RF power handling.

The working group sessions opened with presentations on the technology challenges of each of the technology options, presented by people who have the most experience in each of the technology options. The first presentation was on "Technology Challenges for RF Guns as ERL source", by D. Dowell (SLAC). This was a comprehensive and detailed study of RF guns, both normal-conducting (like Dowell's Boeing gun, which is still state-of-the-art for any RF gun for ERLs) and superconducting. It includes valuable data on the performance of CsK_2Sb photocathode, parameter tables and valuable observations. The presentation cannot be well summarized here without doing it severe injustice. The motto of the presentation may be that: "Technical Challenges are Everywhere! RF Gun; NCRF; SRF; Cathodes; Drive Laser; Bunch Compression; Beam Transport." It covers all aspects of the guns and associated systems, as listed in this quotation.

This was followed by "Technology Challenges for DC Guns as ERL source", by C. Sinclair (Cornell). Starting with a bit of history, Sinclair noted that DC guns with Negative Electron Affinity (NEA) photocathodes, operating between ~70 and 350 kV, have been used on many research electron accelerators since 1977. Early sources delivered a few 10 s of μA average current, and a few Coulombs total charge, from a single cathode activation. Current generation NEA cathodes deliver ~10 mA average current, hundreds of Coulombs per illuminated spot, and several useful spots, from a single cathode activation. We started with Coulombs, we are approaching Ampere-hours, and we need to reach Faradays for a practical NEA cathode delivering 100 mA average current from a very HV DC gun.

Next he notes the major challenges: There is essentially no experience operating photoemission guns at very high voltages (500–750 kV). Field emission from electrode structures can lead to voltage breakdown, insulator punch-through, and other less serious problems. Good operational lifetime for high quantum efficiency (QE) photocathodes requires exceptional vacuum conditions — presently at or near the limits of vacuum technology. Lasers supporting 100 mA operation are presently very much state-of-the-art systems.

The presentation covered in detail the particular fronts in the technology:

Vacuum gap state-of-the-art: Modern DC guns aim at or even beyond the state-of-the-art in breakdown field vs. gap size parameter space. Criteria for the ideal material properties for the cathode and anode electrodes are not well understood. Electrode surface smoothness and hardness are important, but not quantified. Field emission can be greatly inhibited by suitable dielectric coatings, but anode coatings are not presently known. Coating real electrode shapes and coating adhesion are key issues.

Ceramic insulator issues: Field emission from cathode electrode structures can cause charging of the ceramic insulator, and ultimately lead to punch-through failures. One needs a ceramic with a bulk resistivity, or a sheet resistivity on the inner surface, which are not easy (or inexpensive) to produce.

NEA photocathodes: Empirical data shows that NEA photocathodes are not harmed by good quality static UHV environments, by illumination with laser light, or by high static electric fields; they do not desorb Cs (and thus do not contaminate gun surfaces), and Cs does not migrate significantly on the cathode surface. Nothing in the process of emitting a photoelectron degrades the photocathode. NEA cathodes are harmed almost exclusively by chemically active residual gases, or ion back bombardment.

Sinclair points out that NEA cathode problems have been solved by operating in a vacuum that is (estimated in the gun) high 10^{-12} to low 10^{-11} mbar range. Massive NEG pumping, coupled with a large sputter-ion pump to remove gases unpumped by NEGs are the promising technological approach, together with air bakeout at 400 C or vacuum firing to ~900 C.

He further points out that NEA (e.g. GaAs) cathodes offer the possibility of very low thermal emittance, and discusses the laser options for this type of photocathode.

In summary, Sinclair points out that the parameters required to operate a 100 mA average current, very high-voltage DC gun with an NEA cathode lifetime >100 h appear to be within reach, but have yet to be demonstrated, and a 1 A average current source with good cathode lifetime will require developments well beyond the present state-of-the-art.

Another talk covered in detail the operating experience of GaAs photocathodes at JLab, in the "Performance of the 10 mA DC GaAs photocathode gun in the JLab IR Upgrade FEL", given by C. Hernandez-Garcia (JLAB). He relates the performance in pulsed operation at 8 mA/pulse (110 pC/bunch) in 16 ms-long pulses at 2 Hz repetition rate, CW operation at 9.1 mA (75 MHz) with 122 pC/bunch and routine delivery of 5 mA CW and pulse current at 135 pC/bunch for FEL operations. Some of the highlights are over 450 C delivered without QE replenishing, 3 months without re-cesiation, about 96% of previous QE is recovered with each re-cesiation. Hernandez-Garcia concludes that the demonstrated 1.1 mA CW with 5.23% QE and 55 mW of laser power on the cathode scales up to 100 mA with 5% QE and 5 W illumination. Halo and lower background vacuum would have to be addressed for +100 mA CW guns.

Open questions are—can the cathode dark current (field emission) stay below ~10 nA at gradients larger than 6 MV/m, (presently operations are at 4.2 MV/m at 350 kV). He points out that the main sources of field emission may come from the photocathode damage due to ion back-bombardment when the cryo-unit trips off.

Table 1
Photoinjector technology parameters and issues, by the three candidate technologies

	DC Gun	Normal RF	SRF Gun
Max. gradient achieved	4.3 MV/m	6 MV/m	32 MV/m
Max. gradient planned	> 7 MV/m	10 MV/m	> 20 MV/m
Max. current demonstrated	10 mA	128 mA at 25% DF	1 mA
Max. current planned	1000 mA	1000 mA	500 mA
Issues	Field emission, vacuum, ion back-bombardment	Thermal management, vacuum	Cathode thermal management, contamination of SRF cavity

Two SRF guns have been successfully tested recently (in addition to work by Achim Michalke in Wuppertal about a dozen years ago [1]).

Technology Challenges for SRF Guns as ERL Source in View of BNL Work, A. Burrill (BNL). Burrill reports about the design, fabrication and commissioning of a 703.75 MHz SRF photoinjector with a retractable multi-alkali photocathode designed to deliver 0.5 A average current at 50% duty factor is the present undertaking of Advanced Energy Systems and the electron cooling group in the Collider Accelerator Division of Brookhaven National Labs. This photoinjector represents the state-of-the-art in photoinjector technology, orders of magnitude beyond the presently available technology, and should be commissioned by 2007. The R&D effort presently underway will address the numerous technological challenges that must be met for this project to succeed. These include the novel cavity design, the challenges of inserting and operating a multi-alkali photocathode in the photoinjector at these high average currents, and the design and installation of a laser system capable of delivering the required 10 s of watts of laser power at 50% duty factor to make this photoinjector operational.

Technology Challenges for SRF Guns as ERL Source in View of Rossendorf Work, D. Janssen (Rossendorf). This presentation comes after successful tests of a SRF gun with a superconducting half-cell cavity, and while a new SRF photoinjector for cw operation at the ELBE linac is under development. It discusses the design of the injector, the technological challenges of different components, the status of manufacturing and the expected parameters. The conclusion from the successful operation of the SRF injector with a half-cell cavity in 2002 at the Forschungszentrum Rossendorf is addressing the crucial question if the photocathode inside the superconducting cavity reduces the quality factor due to particle pollution. During about 200 h operation time, such an effect was not seen using $CsTe_2$ cathodes. It also demonstrates convincingly that a reliable mechanism for inserting a normal-conducting cathode stem into a superconducting cavity does not affect the good performance of the SRF cavity. Following this initial success the Rossendorf group embarked on the design and production of a $3\frac{1}{2}$ cell gun which has also various other improvements for getting the smallest emittance out of the device, including careful shape optimization, bunch focusing by a high-order RF mode, symmetrized input coupler and improved tuner system.

An new approach which attempts to bridge the properties of normal and super conducting RF guns was presented in "Novel, Hybrid (Normal-Superconducting) RF Injector for High-Average-Current Electron Sources", by D. Nguyen (LANL) argues that normal conducting RF guns suffer from ohmic loss which scales with $(\text{gradient})^2$. Using a high gradient multi-gradient multi-cell cavity leads to large ohmic losses and requires careful thermal management. Thermal distortion in a multi-cell cavity leads to cavity detuning and loss of RF field flatness. High Q.E. photocathodes are poisoned by contaminations desorbed from the heated cavity walls. On the other hand, superconducting guns suffer from the difficulty of applying a magnetic field for emittance compensation near the cathode, and that operating a semiconductor cathode at low temperature in an SRF cavity leads to low Q.E., and that debris released from semiconductor cathodes could quench the SRF cavities. He offers a solution—a hybrid gun, in which the first $1\frac{1}{2}$ cells are normal conducting, followed very closely by an SRF booster. This has the advantages of cryo-pumping reducing cathode contamination, ohmic loss is reduced with only 1.5 cell NC injector, the gun can now admit a solenoid field for emittance compensation at high bunch charge, and the NC cathode is isolated from SRF cavities, allowing the semiconductor cathode to operate at room temperature.

In conclusion of this section, Table 1 shows a summary of the properties of the three main technology choices for ERL guns.

3. Beam dynamics in the gun and injector

The beam dynamics in the gun and injector are complicated by the low energy (starting actually non-relativistic near the cathode) and the resultant strong space–charge interaction, the process of emittance compensation that starts in the gun and mostly completes in the injector. The aspect ratio of the bunch, which influences its beam dynamics, changes over a large range due to the large relative change in energy. Whatever non-uniformity there is in the charge distribution of the bunch will evolve within a fraction of a plasma oscillation, and that takes place also in the gun and injector area. The merging of the low-energy beam from the injector and the returning ERL high-energy beam at the linac entrance has significant consequences to the beam dynamics of the machine.

To cover this wide range of beam dynamics issues we heard a talk on "Emittance Compensation Theory Overview", by J. Rosenzweig (UCLA). The speaker explained the theory of emittance compensation and the invariant envelope concept which the speaker and L. Serafini (INFN) developed. Additional work on the subject was presented as "Comment on the invariant envelope solution in RF photoinjectors", by C. Wang (ANL). The conclusion was that the theory of emittance compensation is a powerful tool that allows one a rational design of a gun and injector for best emittance performance.

The beam merger presents a new problem, a nonlinear coupling between the longitudinal motion and transverse motion in the bending plane. This issue was discussed in "Optimal merger optics and matching to the main linac", by V. Litvinenko (BNL). The authors offer a new approach to beam merging by devising a system with bi-lateral symmetry, the so-called "zigzag" merger. This idea provides for the first time a solution to how to merge high charge bunches into the accelerator without blowing up the bend-plane emittance. We also heard a presentation on "Space charge, CSR, and optimal merger energy", by S. Lidia (LBNL), made in the framework of the LUX project parameters. He concluded that the optimal energy is linked to reducing space charge effects in the compressor, and that CSR induced emittance growth and longitudinal instabilities considerations dominate the design of the arcs and injection lattice. For high-energy machines the slice energy spread from the photoinjector beam is too small to prevent longitudinal instability growth, and thus laser "heating" techniques are useful to introduce a correlated energy spread at high frequency that acts as an uncorrelated spread at frequencies with large gain in the longitudinal CSR instability.

Given the complexity of the photoinjector physics and the large number of parameters that must be adjusted, getting an optimal performance out of this system is a daunting task. Therefore the working group participants were very encouraged by two presentations on automated optimization procedures that were developed for this purpose. The first was "Multivariate optimization of Injector Performance", by I. Bazarov (Cornell), which described the application of a genetic algorithm and parallel computing for the optimization, noting its power and the sometimes unexpected (by simple physics intuition) optimal values for some of the parameters. The second talk was on "Multiple-parameter optimization of ERL injector", given by R. Hajima (JAERI), a similar task using optimization with PARMELA, step-by-step optimization by down-hill simplex and all-at-once optimization by simulated annealing.

4. The cathode and laser package

The photocathode and laser are very much related subjects, since the QE of the photocathode and the wavelength at which it reaches this QE determine the power of the laser, which may or may not be realizable. The lifetime of the cathode and the vacuum quality that is necessary to achieve this lifetime are also critical considerations, since some gun systems cannot be expected to achieve the vacuum level necessary for some cathodes. A few ground rules were elucidated in the working group. First, it has been agreed that the operational wavelength of the photocathode should be in the visible window; otherwise the conversion of the laser light to shorter wavelength (UV) would present a crucial toll on the overall laser power requirements. The uniformity of the photocathode emission is also critical, since its affects the emittance of the beam. Finally, we note the emergence of a new approach to photocathodes, the diamond amplified photocathode, which was described by a few speakers. The recent experimental results obtained at BNL provide hope that this cathode system is around the corner.

A talk on the "Photocathode options and state-of-the-art", Srinivasan–Rao (BNL), presented the requirements from a photocathode: High, uniform QE preferably in fundamental of laser/visible; long life time-tolerant to contamination, ion bombardment; large charge deliverable; prompt response ~100 fs electron bunch; short recovery time; operable in High Vacuum; operable in High Field; does not contaminate the injector environment; cryogenic operation; ease of preparation, transport, transfer. She walked the audience through the various photocathodes available, both well tried and new concepts. When all above requirements are applied, only very few candidates remain. She also described the diamond amplified photocathode and showed that this approach fulfils all the requirements and also provides extremely high QE, a few hundred times higher than the base photocathode being amplified. Srinivasan–Rao finished by describing some potential laser systems. She concluded that commercial systems are tantalizingly close to meeting a lot of the requirements, however beam shaping and stability requirements may push the parameters to beyond commercial systems, and even if commercial systems are available, project specific custom modification will be needed.

The diamond amplified photocathode system was described in detail in the talk on "Secondary emission cathodes", by X. Chang (BNL). Following a description of the concept and how it works to provide an extremely long lifetime of the cathode by encapsulation in a hermetically sealed package, how it also serves to protect the gun from the photocathode material, and the specific properties of diamond which are essential for this application, such as extremely good thermal conductivity and easy application of NEA. Chang finished by presenting experimental measurements on gain of up to a few hundreds and transmission through thick diamonds.

A new program at JAERI also embraces the diamond amplification scheme of BNL, as described in "Diamond electron cathodes", by E. Minehara (JAERI). The speaker presented the equipment and approach taken by JAERI towards gallium arsenide (GaAs) photocathodes in extreme-high vacuum and diamond amplification systems. We heard more of the JAERI program in the talk "DC gun test bench and superlattice GaAs as photocathode", given by T. Nishitani (JAERI). The fabrication of superlattice GaAs photocathodes is pursued using Molecular Beam Epitaxy, leading to a photocathode DC-gun which satisfies the requirement of long life-time performance.

Simulations predict that a superlattice is expected to have higher QE and smaller thermal emittance than a bulk GaAs.

The discussions yielded a list of available photocathodes as a function of required current:

Over 100 mA: Cs:GaAs (demonstrated 9 mA CW in a DC gun at JLab), K2CsSb (demonstrated 128 mA at 25% duty factor, in a copper RF gun at Boeing), Cs3Sb.

Over 10 mA: Cs: GaAs(polarized), and Cs2Te.

Over 1 mA: Metals, Dispenser cathodes.

Technologies to watch (not demonstrated in injectors yet): Cs dispenser cathode, Cs:GaAsP, Cs:GaN, Diamond amplified photocathodes.

Switching to the associated lasers for photocathodes, the "Laser State-of-the-art: Performance, Stability and Programmable Repetition Rate" was presented by M. Shinn (JLAB). Shinn presented the current laser development, which is specified to deliver ~135 pC charge/bunch, or 100 mA average current. To achieve this current, they need a laser with these specs: Power: ~30 W, at 748.5 MHz, 532 nm. This assumes NEA GaAs with 1% QE at 532 nm. Pulse-width: ~30 ps FWHM. Amplitude jitter <0.5% p–p. Timing jitter <1 ps RMS w.r.t. RF master oscillator. Following the description of the approach and the hardware, she concluded that a drive laser system can be a reliable component of an accelerator. Economics (telecom and material processing) are driving the state-of-the-art in the right direction to provide laser systems for 100 mA ERLs. These systems will probably never be catalog items, since the specified pulse repetition frequencies are not really interesting to major laser manufactures. However, "boutique" laser vendors probably can provide what is needed.

The discussions on beam dynamics and beam quality stressed the need for optimal laser shape. In the past couple of years the technology of laser shaping for photoinjector applications became available. This was exemplified by H. Tomizawa (Spring-8), who reported on "Laser Pulse Shaping for Photoinjectors". Tomizawa described an impressive system (developed, built and operated essentially by one person) that does laser shaping in 3-D by a variety of advanced optical methods. He concluded that automatic (program driven) shaping of the spatial profile with a deformable mirror and genetic algorithm was successful, achieving either Gaussian or flat-top distributions. However, it takes 1 h for the system to reach the optimum. He reported that when the spatial profile was improved, the gun emittance was reduced from 6 μm down to 2 μm. Automatic shaping of temporal profile with fused-silica-based spatial light modulator (SLM) was achieved, yielding rectangular pulse of 2–12 ps with rise-time of 800 fs. Future plans call for compensating any kind of distortion with SLM (Temporal) using the electron beam data. He notes that both profiles can be shaped with fiber bundles, even in the UV.

The beam dynamics discussion also pointed out that tri-uniform (or "beer-can") distributions, while they provide improved emittance over Gaussian distributions, are still not ideal. One desires distributions that have linear space–charge dependence in the bunch as well as being stationary under the beam acceleration and transport, and an elliptical distribution comes closer to that ideal. This was emphasized in the talk on "Optimal Distributions for Photoinjector RF Guns", by C. Limborg-Deprey (SLAC). She has shown results of simulations that compare the slice-by-slice emittance performance of various distributions, showing that an elliptical distribution outperforms the "beer-can" distribution. An additional advantage is a much decreased sensitivity to errors. In addition, she described a spectral control technique that exists in the IR and may be even achieved in the UV, leading to arbitrary 3-D shaping using four-gratings with masking arrays in a dispersive environment. The principle uses a highly chirped beam with dual projections, time and horizontal shaping on a 2D masking matrix, followed by time and vertical masking.

The discussion led to a list of lasers and their parameters, sorted out by potential ERL applications, which is shown in Table 2.

5. Modeling and computational issues

The beam dynamics of the ERL photoinjector at non-negligible bunch charges is dominated by emittance compensation. Some of this work is being done towards ERL-driven X-ray FELs.

Significant work has been done towards the design of an ERL with 1 MHz repetition rate at 1 nC per bunch driving a potential DESY X-ray FEL, using a superconducting RF gun. "Optimization and Beam Dynamics of an SRF Gun" was then presented by M. Ferrario (INFN). Using the Serafini–Rosenzweig invariant envelope approach and a number of simulation codes, Ferrario described a gun capable of excellent performance in terms of beam brightness. Among his points were the following: Emittance compensation by an external solenoid is possible. A 60 MV/m peak field in SC cavity has been already demonstrated. Work is in progress at BNL to demonstrate a lead photocathode directly deposited on the niobium back-wall, and one expects QE~10^{-3} at a laser wavelength

Table 2
List of potential photoinjector lasers and their parameters, sorted out by application

Parameter	Electron cooling	High current ERL	Polarized electron ERL
Current (mA)	500	100	24
PRF (MHz)	28	700	15
Wavelength (nm)	530	530	780
QE (%)	2	2	0.3
Laser system	Yb Fiber MOPA with SHG		Er Fiber MOPA w/ SHG
Cathode power	70	15	30

Table 3
Emittance compensation simulations for 3 possible guns

	Bunch charge	Bunch length[*,#]	Emittance[*,+]	Cathode[&]	Peak field
Units	nC	ps	μm	meV	MV/m
RF gun	1/0.2	2.8/1.7	0.72/0.3	Copper, 700	S-band, 120
DC gun	1/0.1	3/3	0.8/0.14	GaAs, 35	15
SRF gun	1/0.1	5.7/2.7	0.8/0.23	Metallic, 184	L-band, 60

Symbol key for this table: [*] RMS; [#] Compressed; [+] Normalized; [&] Material and assumed electron temperature.

of 200 nm, which is reasonable for the 1 mA current planned.

Another potential ERL-based FEL was described in the talk ‘‘Conceptual design for the KEK–ERL test accelerator’’, by T. Suwada (KEK). Suwada informed the workshop that a conceptual pre-injector design study for the KEK–ERL test accelerator is under development. This work is done using a new, fast simulation code. The new code describes semi-analytically the time evolution of a bunch motion in the transverse and longitudinal phase spaces. Agreement with PARMELA is better than 30% longitudinally, but only qualitative transversally. A demonstration ERL at 200-MeV is being designed.

An unorthodox approach to moderate average beam current (1–50 mA) guns was presented in the talk ‘‘Field-Emission Cathode Gating for RF Electron Guns’’, given by J. Lewellen (ANL). He compared the various photocathode options and their salient advantages and disadvantages. Lewellen then described a gun without a laser, which still produces well defined, short electron bunches emitted at the optimum phase for emission in each RF cycle. The idea is to use field emission cathode, which is capable of high-current densities (and thus high brightness) from small emitters in the gun. While this idea has been contemplated before, the breakthrough in this novel approach is a particular superposition of a harmonic frequency on top of the fundamental. By a proper selection of the phase and amplitude of the harmonic relative to the fundamental, one creates a waveform that peaks at one place in a way to produce emission in for a short time in the right phase relative to the fundamental. The author has shown simulations of the current and emittance of such a gun, which is aimed at relatively high-volume applications such as electron microscopy.

A comparison done in this Working Group yielded an interesting result summarized in Table 3. This table shows calculated emittances possible from the three types: NCRF, DC and SRF. Low thermal emittance of the cathode allows larger illuminated laser spot and consequently reduced space–space charge at the cathode. Emittance compensation is efficient in all three gun types. As a result, comparable emittances at the end of the injector can be achieved despite very different electric field values in the guns.

6. Magnetized beams and polarization

Some of the future ERL applications are rather specialized and require specialized electron sources. These include polarized electrons for electron–hadron colliders and magnetized electrons for electron cooling of stored hadron beams.

The subject of ‘‘Polarized cathodes and the prospects for high current’’ was presented by M. Poelker (JLAB). The author posed the question as follows: ‘‘What will it take to provide 1 mA at 85% polarization?’’ Given that this represents an improvement of state-of-the-art by factor of 5–10, it is a step in the right direction, yet quite modest compared to the requirements of 30 mA for the ELIC collider, which is planned with beam circulation, and even smaller in comparison to the requirements of eRHIC, based on a few 100 mA.

To achieve this initial step Poelker calls for good photocathode material, (two commercial vendors exist); high power mode locked Ti–Sapphire lasers with GHz repetition rate, (one commercial vendor for rep rates to 500 MHz exists); good gun lifetime, which call for good static vacuum (1×10^{-11} Torr, using NEGs + ion pumps);

maintain the good vacuum while delivering beam (deliver the good electrons and eliminate the bad electrons or at least ensure they hit the vacuum chamber walls far from the gun); and last but not least reliable hardware: lasers, gun and diagnostics. He concludes that only superlattice photocathodes have demonstrated polarization $>80\%$, and only superlattice photocathodes can (in principle) provide 1 mA with existing commercial modelocked Ti–Sapphire lasers. However, superlattice photocathodes have good initial QE but lifetime at CEBAF has not been as good as for strained GaAs, the QE falls with increasing laser power. It is clear that more experience is needed.

For scaling to even higher currents, he concludes that gun lifetime is dominated by ion back-bombardment, so it is reasonable to assume lifetime proportional to current density. Thus the approach to higher currents is to use a large laser spot to drive the gun. This keeps the charge density small, and one may expect to enjoy the same charge density lifetime, despite higher average current operation, with existing vacuum technology. To be more specific, Matt assumes the use of 1 cm diameter laser spot at the photocathode. From CEBAF experience, at 2.5 mA gun current, they deliver 9 C/h, 216 C/week. Charge is delivered until QE falls to 1/e of initial value. There is a need to test the scalability of charge lifetime with laser spot diameter, by measuring charge lifetime vs. laser spot diameter in the laboratory. Yet, the CEBAF beam lifetime estimate is $100\,000\,\mathrm{C/cm^2} * 1\,\mathrm{week}/216\,\mathrm{C} * 3.14\quad(0.5\,\mathrm{cm})^2 = 360\,\mathrm{weeks}!$ This corresponds to 36 weeks lifetime at 25 mA, or even consider 3.6 weeks at 250 mA, all assuming that the vacuum level is maintained, which means tight control over beam losses in the vicinity of the gun.

The "Production of magnetized beams in photoinjectors", was presented by P. Piot (FNAL). He maintains that understanding the generation of angular-momentum dominated e-beams is a first step toward understanding (and optimizing) the flat beam transformation, which has multiple applications outside an ERL such as beam production towards the ILC at FNAL and the LUX proposal at LBNL, and for ERLs such as the RHIC e-cooling. Possible techniques for the production of angular momentum dominated beams are by the application of non-zero axial magnetic field on the cathode and ribbon laser transformed into a round beam (Derbenev transform). Phillip described the work at his FNAL laboratory on the generation of angular-momentum-dominated electron beams in a photo-injector and studies of the conservation of angular momentum along the beam-line. In their case (up to ~2 nC) the beam dynamics is dominated by angular momentum. One diagnostic approach (as well as an application) is to produce a flat beam using a quadrupole triplet. He has shown an excellent agreement of the measurements with simulations, and the production of a very nice emittance ratio of $\varepsilon_x/\varepsilon_y = 85 \pm 5$.

Another item mentioned in this presentation was a plan to test a polarized electron source injector for the ILC based on a cryogenic (but not superconducting) RF gun. FNAL's position is that a DC gun cannot provide a high enough electric field. Polarized injectors have complicated bunching scheme (being a compromise between emittance and bunch length), thus a higher field on the cathode would help. This program will be watched with a lot of interest.

Acknowledgments

We would like to thank the participants of Working Group 1, the various speakers and the organizers of the ERL Workshop. This work was done under the auspices of the US Department of Energy, the Office of Naval Research and the National Science Foundation.

References

[1] A. Michalke, AIP Conf. Proc. 279 (1993) 761.