Development of high brightness, high repetition rate photoelectron injectors at STFC Daresbury Laboratory

B L Militsyn1, I Burrows1, R J Cash1, N Chanlek1,3, B D Fell1, L B Jones1, S N Kosolobov2, J W McKenzie1, K J Middleman1, H E Scheibler2 and A S Terekhov2

1STFC Daresbury Laboratory, Warrington, WA4 4AD, UK
2Institute of Semiconductor Physics SB RAS, Novosibirsk, 630090, Russia
3University of Manchester, Manchester, M13 9PL, UK

E-mail: boris.militsyn@stfc.ac.uk

Abstract. Accelerator drivers for Energy Recovery Linac (ERL) and Free-Electron Laser (FEL) based light sources demand electron injectors which deliver high brightness bunches on the several hundreds of picocoulomb scale, at repetition rates between 1 MHz and 1 GHz (or higher), corresponding to an average current between 0.1 and 100 mA. Simultaneous satisfaction of these injector requirements is considerably beyond the current state-of-the-art. Daresbury Laboratory is concentrating efforts on the development of high average current III-V and X\textsubscript{n}Y\textsubscript{3-n}Sb photocathode-based DC and SRF photocathode guns for ERL applications. The ultimate goal of this research is their integration with the ALICE ERL.

1. Introduction

Low emittance high repetition rate electron beams are desired for several future Linac, Energy Recovery Linac (ERL) and Free-Electron Laser (FEL) based light source projects, including the UK’s New Light Source (NLS) [1]. Currently operational linac-based FELs such as LCLS [2] and FLASH [3] use 1½ cell pulsed normal conducting RF guns operating at the frequency of the main linac. The LCLS S-band gun is powered by a short 2 µs RF pulse which permits operation in single pulse or short train mode. The LCLS injector has experimentally demonstrated beams with emittance values down to 0.3 mm mrad; however, its duty factor is limited by repetition rate due to cavity heating. For a normal conducting RF gun, the 1 ms duration of the RF pulse at FLASH is unusually high, though this permits gun operation in the long train pulse mode and at a pulse frequency in the train of 1 MHz which approaches a duty factor of 1%. Electron drivers of new generation soft X-ray FELs like UK’s NLS, Wisconsin FEL and Berkeley FEL projects require operation at a repetition rate of 1 MHz or higher, delivering bunches with a charge of up to 1 nC. Injectors for those machines cannot be realised on the basis of traditional L- and S-band normal-conductive technology. This duty factor can be increased by using either DC or relatively-low frequency NCRF gun technology. The development of SRF technology raises the possibility of building CW electron guns.

The demands of new ERL projects are even higher than those examples given. Typical repetition rates vary around the linac frequencies with a typical bunch charge of 77 pC to deliver an average current of 100 mA. These current values are stated in the design of the Cornell University ERL [4], the BerlinPro machine [5] and others. In the framework of our ongoing project, Daresbury Laboratory is concentrating on the development of a macropulse photoinjector for the ALICE ERL, operating at a repetition rate of 81.25 MHz with a bunch charge of 80 pC which equates to 6.5 mA train current, and
a CW photoinjector for the NLS project operating at 1 MHz with a bunch charge of 200 pC equating to an average current of 0.2 mA. An upgrade of ALICE to support CW operation demands average current of 1.6 mA. In Table 1, we summarise demands on the high brightness high repetition rate injectors for the accelerators currently under development in the world.

Table 1. Beam parameters required for high repetition rate injectors.

| Beam Parameter                           | ERL (DL, Cornell, BerlinPro) | X-FELs (X-FEL, NLS) |
|-----------------------------------------|------------------------------|---------------------|
| Beam energy (MeV)                       | 1-10                         | 1-10                |
| Maximum bunch charge (nC)               | 0.1                          | 0.1-1               |
| Bunch transverse emittance (mm mrad)    | 1.0                          | 0.5-1               |
| Maximum bunch repetition rate (MHz)     | 1300                         | 1                   |
| Average current (mA)                    | 10-100                       | 1                   |
| Peak current of injector (kA)           | -                            | 0.1                 |
| Bunch duration (ps)                     | 20                           | 20                  |

2. Electron emitters

The most critical component of high average current injectors is the photocathode. The minimum emittance which may be obtained from a photocathode with an internal energy $E_i$ is defined by:

$$\epsilon_{\perp,\text{rms}} = \sqrt{x^2+y^2 - x^2} = \sigma_x \sqrt{\frac{2E_i}{3mc^2}}$$

where $\sigma_x = \sqrt{q/\pi \epsilon_c E_c / 2}$ is the minimal rms transverse beam size limited by the 2D charge density of a pancake beam. In Table 2 we summarise the ultimate emittances which may be obtained from a gun built with different technologies utilising photocathodes with $E_i = 1$ eV, this being a typical value for many modern photocathodes operating in pulsed mode.

Table 2. Ultimate achievable emittance for different gun technologies.

| Technology | Cathode field strength [MV/m] | Achievable emittance at a bunch charge [mm mrad] |
|------------|-------------------------------|-----------------------------------------------|
|            |                               | 0.01 nC | 0.1 nC | 1.0 nC |
| DC gun     | 10                            | 0.11    | 0.34   | 1.08   |
| VHF gun    | 20                            | 0.08    | 0.24   | 0.77   |
| L-band gun | 50                            | 0.05    | 0.15   | 0.48   |
| S-band gun | 100                           | 0.03    | 0.11   | 0.34   |

The ALICE ERL at Daresbury operates in a pulse-train mode with a train current of 6.5 mA generated by a GaAs photocathode. Significant effort at the Laboratory is focused on the development of medium and high current photocathodes suitable for operation in the 1-10 mA current range.

2.1. III-V photocathode development

Historically, III-V family photocathodes such as GaAs, GaAsP, InGaAsP were used mainly in DC guns for the production of polarised electrons. As grown, these materials have a positive electron affinity (PEA), which is 4.8 eV for GaAs. In order to make GaAs photocathodes able to emit electrons when illuminated by 532 nm light, the electron affinity should be reduced to less than 1 eV - or even brought to a negative value. This activation process basically comprises deposition onto an atomically-clean photocathode surface of thin layers of Cs and an oxidant, typically O$_2$ or NF$_3$. Before the activation, the surface of the photocathode is chemically etched and heat cleaned in order to remove As and Ga oxides.
Recent measurements of the QE spectra indicate that GaAs activated to PEA with a QE of a few per cent and illuminated with green light is capable of picosecond level response times. This is enough to deliver bunches with a charge of several dozen pC. Figure 1 shows QE spectra for PEA GaAs photocathodes activated with Cs only to different levels of Cs coverage. The position of low energy threshold corresponds to the energy gap $E_g$ for GaAs, and the position of $I_{hot}$ corresponds to the vacuum level. The energy difference between these two thresholds is equal to the effective electron affinity. Figure 1 also shows the measured longitudinal energy distribution of electrons emitted from a PEA GaAs photocathode, demonstrating that when illuminated with green light, the energy spread is relatively large.

GaAs photocathodes place extremely high demands on operational vacuum conditions as they are extremely sensitive to the presence of oxidants in the residual atmosphere. For example the 1/e lifetime of GaAs does not exceed $2 \cdot 10^{-8}$ mbar s of oxygen exposition [6]. The pressure in a typical GaAs gun is of the order of $10^{-11}$ mbar. Low operational lifetime is also an issue because the dominant GaAs degradation mode is bombardment of the cathode surface by back-streaming ions.

2.2. Alkali photocathode development

A good alternative to GaAs for operation at high and medium average currents may be antimonide-
based photocathodes. Alkali photocathodes (AP) operate in visible and near-infrared light and demonstrate quantum efficiency of up to 80 mA/W or 18% at 532 nm wavelength. As most of these photocathodes exhibit Positive Electron Affinity (PEA), they are able to maintain fast response time (in the ps range on the metal substrate) even at high quantum efficiency levels in contrast to Negative Electron Affinity (NEA) photocathodes like GaAs. The dark lifetime of these photocathodes is three orders of magnitude better than GaAs [7], and the vacuum demands are far less stringent. However, their operational lifetime, or lifetime under ion back-bombardment, is unknown, and this has to be investigated. AP photocathodes have been used in photomultiplier tube (PMT) industry for many years, and this technology is well developed. AP have been used in an accelerator injector only once: in 1994 the Boeing project used an AP which set the world record of 32 mA current in an RF CW gun [8]. Presently, AP are considered as the photocathode of choice where a current exceeding 1 mA is required, such as ERLs (BerlinPro, BNL) and high repetition rate FELs (LBNL, Wisconsin). Cornell University, JLab and other organization are also interested in the development of the AP technology. Daresbury Laboratory plans to begin work on AP in the next financial year.

3. DC photocathode guns based photoinjectors

High voltage DC electron guns with GaAs photocathodes are considered as the gun of choice by a number of laboratories worldwide as injectors for ERL-based free electron lasers due to their potential to deliver beams of high average current (up to 100 mA in CW mode) with a relatively low normalized emittance of a few mm mrad. Since the minimum emittance, $\epsilon_{\text{min}}$, of the delivered electron beam is related to the electric field strength on the cathode surface as $\sim 1/\sqrt{E_c}$, there is a strong motivation for increasing gun operational voltages. At TJNAF [9], Daresbury Laboratory [10] and JAEA/KEK [11], the gun power supplies are rated to 500 kV whilst the Cornell University injector [4] is rated to 750 kV.

3.1. ALICE Gun

The ALICE electron gun at Daresbury Laboratory is a modified version of the TJNAF design developed for Infra-Red FEL, and is described in detail elsewhere [12]. The main modification to the original TJNAF gun design is the use of a single large ceramic with bulk-doped controlled resistivity as the high voltage insulator. Whilst initially successful, with routine conditioning to 450 kV (up to a maximum of 485 kV), the long-term reliability of the brazing joints under load due to thermal cycling during baking has been poor. A collaboration between Daresbury Laboratory, TJNAF and Cornell University has resulted in design of an insulator with a modified taper at the brazed joint. This insulator has been manufactured, and is planned for installation as part of the gun upgrade.

3.2. ALICE Gun Upgrade

An upgrade to the ALICE gun is currently underway, and is schedule for installation in 2011. This will involve the installation of a new high voltage insulator, the development of new photocathodes, the addition of an external “load-lock” photocathode preparation facility, and a side-loading transport mechanism for inserting extract photodcathodes to/from the gun. An extended gun beamline incorporating a suite of diagnostics useful both for ALICE operations and the testing of different photocathodes is also under consideration and is described in [13]. A detailed description of the gun upgrade and photocathode preparation facility may be found in [14-15].

ALICE currently uses GaAs photocathodes with an exposed diameter of 25 mm. The new cathode assembly of the gun, however, has been designed to accommodate photocathodes with an emission surface diameter of 10 mm. This is because the laser only illuminates an area ~ 4 mm in diameter and a smaller active area could help reduce the beam halo. New photocathodes designed for ALICE are shown in Figure 2. The preparation facility allows a variety of III-V photocathodes to be activated and tested in the ALICE photoinjector, these having various active layer composition, thickness, and electron affinity. Beam dynamics simulations have shown that the ultimate beam emittance which may be obtained from the gun is less than 1.0 mm mrad [15].
4. SRF gun based photoinjectors

The next project developed within the Daresbury photoinjector program framework is the design of a high repetition rate high brightness photoinjector for ongoing the New Light Source project. The machine requires 200 pC bunches at a repetition rate of 1 MHz, equating to an average current of 0.2 mA. The emittance of this beam should be as low as 0.5 mm mrad. At 1 MHz CW, existing UV laser systems are not able to drive metallic photocathodes, so Cs$_2$Te alkali photocathodes are considered instead. A 3½ cell SRF gun operating with a Cs$_2$Te photocathode is under commissioning at FZD [16] with a goal to deliver 1 mA average current.

To reduce complexity of the injector, we focus on a single cavity, 1½ Tesla cell design [17]. Recently a prototype of such a cavity was vertically tested to a peak electric field of 40 MV/m [18], and a gun with a field of 50 MV/m is potentially feasible. However, as this is pushing the state-of-the-art, beam dynamics simulations have been carried out at both 40 and 50 MV/m peak fields.

Since the high acceleration field in the SRF gun prevents bunch expansion and keeps bunch length close to that of the initial laser pulse, a separate buncher is not required. ASTRA [19] simulations have been carried out with a laser pulse having a 1 mm diameter flat-top transverse profile and a 30 ps flat-top temporal profile, with rise and fall times of 2 ps. Initial thermal energy of 0.7 eV was included, based on the use of a Cs$_2$Te photocathode. After the gun cavity, there is an emittance compensation solenoid which may be superconducting so that it can be contained within the gun cryostat. An alternative is to have a second cavity operating in a TE mode which provides a field profile similar to that of a solenoid. This would require additional cavity design and a dedicated RF power supply locked to the gun RF, due to the different frequency to the TM accelerating mode.

![Figure 3. Bunch properties for the injector at the exit of the first linac module, with gun peak fields of 50 MV/m.](image)

At a peak field of 50 MV/m, the gun accelerates the electron beam to 4.5 MeV. Operation at 40 MV/m reduces this energy to 3.6 MeV. The gun is operated at a phase of +3° from crest for 50 MV/m and +1° for 40 MV/m. These phases were chosen for optimal emittance. Following the solenoid, the beam is then injected into the first module of the main linac where it is further accelerated to 130 MeV. The linac module contains eight 9-cell Tesla cavities at a frequency of 1.3 GHz. These are operated at an average accelerating gradient of 15 MV/m. The first cavity is operated at a phase of -40°.
remaining cavities are then operated at +4.5° in order to compensate the energy chirp. Figure 3 shows the final distribution of the 200 pC bunch at the exit of the first linac module for ASTRA simulations at 50 MV/m. The flat current profile has duration of 35 ps and the slice emittance around 0.3 mm mrad throughout the bunch.

5. Summary
Ongoing and perspective projects stimulate development of high brightness high repetition rate injector at STFC Daresbury Laboratory. The GaAs-based 350 kV DC gun for ALICE ERL has been operational since August 2006. Gun upgrade stimulated development of a photocathode preparation facility has been recently successfully commissioned. The photocathodes have been activated with a maximum QE of 15% measured at 635 nm. Work on NLS project motivates SRF technology in the Laboratory and on the basis of this technology development of a high brightness high repetition rate gun.

6. References
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