ISBN: 978-3-95450-217-2 doi:10.18429/JACoW-ERL2019-WEPNEC13

PRELIMINARY INVESTIGATIONS AND PRE-RESEARCH SCHEME OF HIGH AVERAGE CURRENT ELECTRON INJECTORS AT IMP

Q.T. Zhao†, Z.M. Zhang, J.C. Yang, H.W. Zhao
Institute of modern physics, Chinese academy of sciences, Lanzhou, China

Abstract

High average current electron injectors are desired by high average beam power SRF linacs. With respect to the different linac applications, different beam qualities are required. Two kinds of the electron guns are planned for future projects at IMP, one is thermionic electron gun dedicated for high average current, and another one is photocathode gun for high average current and high beam quality or even with high polarization. Current status and development of the high average current electron sources are investigated and summarized. The thermionic gun studies are planned and the feasible types of guns for the future Electron ion collider of China (EicC) project are also proposed. The pre-research of these required electron injectors is schemed, which will be the start of high average current and high-quality electron source development at Institute of modern physics (IMP), Chinese academy of sciences (CAS).

INTRODUCTION

High repetition rate, high average current electron injectors are required by many high average power superconducting radio frequency (SRF) electron linacs. These high average power SRF linacs are dedicated for different applications, such as high average power free-electron lasers (FEL) [1], medical isotope production [2], industry application [3], electron ion collider (EIC) [4], electron cooling for high energy heavy ions [5] and so on. With respect to different applications mentioned above, the requirements of the beam quality are different. The final beam quality required in the interaction region can be traced back to the requirements on the electron bunches from the injector, the first stage of the SRF linac. The electron injector, beginning with a cathode, is the source of the electrons. The quality, bunch length, and timing of the electrons injected into the first linac cavities are critical to determining the properties of the final high energy electron bunch.

Electron injectors can use several different types of cathodes to generate the electrons. One approach is to use a thermionic cathode, which can produce high average currents, but its shortage is hard to generate short bunch length and high repetition rate electron bunches, and the beam quality is mediate. Another approach is to use a photocathode, which is very popular and the promising method to produce high quality electron bunches and can be used for applications with high quality beam, such as FEL, EIC and electron cooling. However, the thermal issues, short lifetime, and drive-laser average power requirements currently present limitations for high average current photocathode injectors. Another unique advantage of the photocathode injector is capable to generate the polarization electron beam which is required for EIC. The electron gun can be classified into three types by the gun cavities and field modes, high voltage DC type, normal conducting RF and SRF type [6]. Due to the critical thermal loads for the normal conducting RF gun, it is not efficient and suitable for high average current and high average power electron source. Another issue of its poor vacuum condition, the normal conducting RF gun is not suitable for polarization electron source. Therefore, here we mainly talk about the high voltage DC gun and SRF gun.

The SRF linac projects are planned in IMP, one is dedicated with high average power application for medical isotope production and others are planned for EicC project [7], which has two SRF linacs, one requires polarized electron injectors with high beam quality and high polarization rate and another one needs high repetition rate, high bunch charge, high beam quality electron injectors for e-cooling of the high energy heavy ions. Different electron injectors are scheduled for the above projects based on the properties of the different types of the electron injectors. In this paper, we discussed the designed and required injectors' parameters for different application and proposed the solution and study plans of the injectors.

RF MODULATED THERMIONIC CATHODE HIGH VOLTAGE ELECTRON GUN

Due to the ability to generate high average current, long lifetime, and good stability and reliability, the thermionic cathode gun is preferred for many high average powers with mediate beam quality applications, like IR-FEL [8] and medical isotope production [9]. Normally, the thermionic cathode high voltage gun generates the direct current, which should be manipulated to short bunch with chopper and buncher devices, in order to match the RF acceleration. This method is inefficient and costly. Another method is gated the thermionic cathode high voltage DC gun with RF voltage, the generated electron bunch repetition rate is same with the frequency of the RF voltage, which is very convenient to generate the high repetition rate electron bunches, as high as 1 GHz [10]. This kind of gun is also considered to be the possible electron source for energy recovery linacs (ERLs) [11], like ERL based IR-FEL, electron cooling [12].

† Email address: zhaoquantang@impcas.ac.cn

ISBN: 978-3-95450-217-2 doi:10.18429/JACoW-ERL2019-WEPNEC13

The required electron gun parameters for medical isotope production are shown in table 1. With these parameters, the RF modulated thermionic cathode high voltage DC gun is selected due to its optimal properties mentioned above. In addition, it is already successfully used in other labs [13, 14].

Table 1: Designed RF Modulated Thermionic Cathode High Voltage DC Gun Parameters

Beam parameters	Designed values
Beam energy	300 keV
Average current	5 mA
Beam repetition rate (CW)	325 MHz
Bunch charge	16 pC
Energy spread	1%
Normalized rms emittance	<5 mm mrad

The sketch map of the RF modulated thermionic cathode high voltage DC gun is shown in figure 1(a). The voltage applied on the grid is Ug=Uc+Ub+Urf, where the Uc is the cathode voltage (-300 kV), Ub is the biased DC voltage to block the electrons extraction, Urf is the RF voltage used to extracting the electrons when the RF voltage is phased for positive polarization. Furthermore, the RF voltage can be designed with fundamental plus the high order harmonic RF voltage for generating the shorter bunches [15]. From figure 1(b), it is clearly shown that with this method it can generate the shorter bunch length electron beams (conducting angle is smaller).

For this gun design, except the normal challenges for high voltage DC gun, another big challenge is how to feed the RF voltage into the grid between the cathodes. Some lessons learned from TRUMF may be helpful [13]. One method is putting the RF voltage supply on the high voltage platform, which will make the gun body huge. Another method is putting the RF voltage supply on the ground and connected to the grid and cathode by ceramic wave guide and impedance matching network, which is not only used for feeding the RF voltage to the grid, but also for isolating the high voltage from the RF voltage generator. The gun body can be compact with this method. Currently, we planned to use the ceramic wave guide. The RF modulation test studies with 30 kV high voltages are under way. The gun structure design combined with beam dynamics simulation is studying with *SF* [16] and *GPT* [17] code.

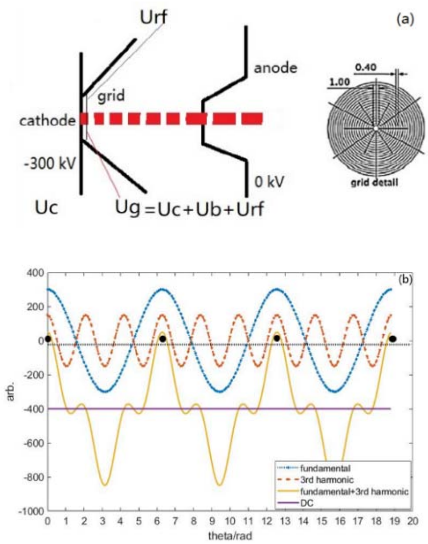

Figure 1: The sketch map and principle of RF modulated thermionic cathode high voltage DC electron gun: (a) principles (b) grid RF voltage for gating the shorter bunch electron emission.

PHOTOCATHODE INJECTORS

A project for a polarized electron-ion collider in China (EicC) is planned based on the high intensity heavy ion accelerator facility (HIAF) [18]. The HIAF is already starting construction. The preliminary design and layout the EicC are shown in figure 2. Two electron injectors are required for the EicC, one is polarized electron beam and another one is for ERL based electron cooling (e-cooler).

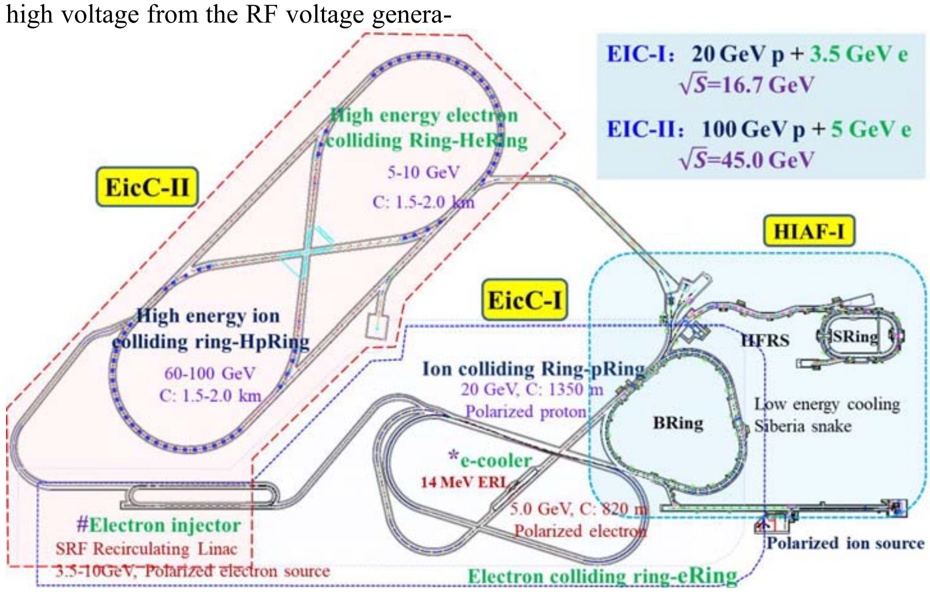

Figure 2: the preliminary blueprint of the EicC project and basic parameters. [Courtesy of J.C. Yang and G.D. Shen].

ISBN: 978-3-95450-217-2 doi:10.18429/JACoW-ERL2019-WEPNEC13

The preliminary electron injector parameters for the polarized electron beam are listed in table 2. Currently, for the polarized electron beam, due to its unique cathode material (GaAs) and some critical demands, especially for the high vacuum (10^{-10}pa) conditions, the high voltage DC photocathode electron gun is the most possible choice [19]. The photocathode for polarized beam is strained GaAs. Currently the QE, lifetime and polarization rate are still big challenges [20]. For high average current polarization electron gun, the cathode problem should be solved firstly. For the high voltage DC photocathode gun, the gun voltage higher is better for generating high quality beam, normally 500 kV is preferred. For polarized electron gun, 300-200 kV is chosen because of lower field emission and beam energy for longer cathode lifetime and easy polarization manipulation [21]. Here we choose 300 kV, the same with thermionic cathode gun. The SRF photocathode gun can produce high average current high-quality electron beam although the technology is not mature. The biggest challenge is the compatibility of the normal conducting cathode and the SRF cavity. The SRF gun for polarized electron source was proposed and tested by putting the GaAs photocathode in the SRF gun cavity but without beam commissioning [22]. There is still a long way to develop the SRF gun properly for polarization electron source.

Table 2: Preliminary Beam Parameters Requirement for EicC Electron Injector

Beam parameters	Required values
Beam energy	6-10 MeV
Bunch charge	0.1 – 0.5 nC
Micro-pulse repetition rate	30 MHz
Macro pulse length	50 us
Macro pulse repetition rate	20 Hz
Normalized rms emittance	<2 mm mrad
rms beam energy spread	<0.1%
rms bunch length	<50 ps
polarization	>80%

A high voltage DC photoemission electron gun followed by an SRF accelerating module is presently the best solution for generating high average power electron beams of moderate bunch charge, particularly for energy recovery linac. The general conceptual DC/SRF booster injector layout is shown in figure 3.

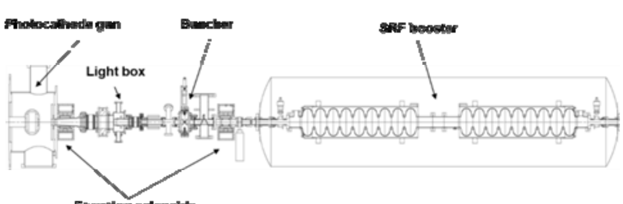

Figure 3: DC/SRF booster injector general layout [23].

The preliminary electron injectors' parameters for electron cooling ERL are listed in table 3. It requires high bunch charge, high repetition rate and high-quality CW operation mode specially. With high voltage DC photocathode gun, the bunch charge is mediate due to limited field gradient at cathode, normally the bunch charge less than 1 nC and currently the highest record is 2 nC [24]. Another potential type of electron source is SRF gun, which is capable to generate high bunch charge, for example BNL 112 MHz quarter ware resonator (QWR) SRF gun, the bunch charge can be as high as 10.7 nC [25, 26]. However, the SRF gun technology is still under development. Other critical parameters are the low emittance and small energy spread, which should be cared from beginning of the beam dynamics design. For electron cooling ERL injector, the QWR SRF photocathode gun is considered especially for high bunch charge. The "green" cathode is most promising for high average current electron source due to the high QE and high efficiency laser technology [27, 28]. Two types of photocathodes, GaAs (polarization and no polarization) and Cs-K-Sb are scheduled to be studied in the future.

Table 3: Preliminary Electron Injector Beam Parameters Requirement for EicC Electron Cooling

Beam parameters	Required values
Beam energy	6 MeV
Bunch charge	4 nC
rms bunch length	100 ps
Pulse repetition rate	0.3 – 3 MHz
Normalized rms emittance	<2.5 mm mrad
rms energy spread	$<5\times10^{-4}$

For the electron injector talked above, some common critical technologies are the same. For high voltage DC gun, thermionic cathode or photocathode, the high voltage supply and high voltage platform is same. For high voltage DC photocathode gun and SRF photocathode gun, photocathode fabrication and test system, laser system can be shared. Furthermore, for characteristic the injectors beam parameters, the test beam line is also proposed. Therefore, it is essential to set up an injector test facility for characteristic the beam parameters of different guns. The conceptual design and layout of the high average current electron injector lab is shown in figure 4, some auxiliary system can be reused for different gun test, such as booster, diagnostics, beam dump and so on.

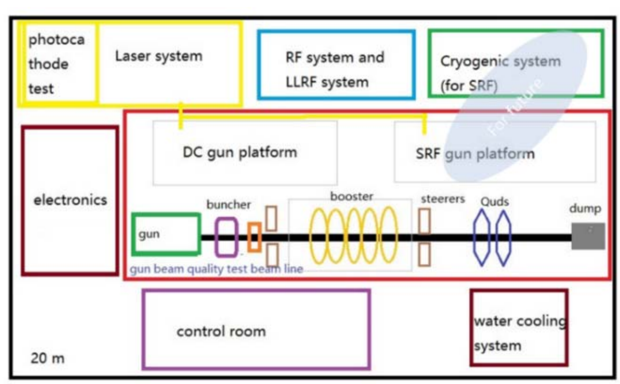

Figure 4: The conceptual design and layout of the high average current electron injector test lab.

SUMMARY

The high average current electron injectors' requirements for IMP projects are listed and discussed. The high voltage DC high average current injectors will be the first step to develop and start with RF modulated thermionic cathode type. The solution for polarized electron injector and electron cooling ERL injector is proposed and the difficulties to be conquered are also discussed. Furthermore, the high average current electron injector lab conceptual design and layout is shown and essential for test of different guns. The high voltage gun geometry design combined with beam dynamics optimization is under way and the design results will be reported soon.

REFERENCES

[1] D. Nölle, "COMMISSIONING OF THE EUROPEAN XFEL", *in Proc. of LINAC'18*, Beijing, Sep. 2018, pp. 994-999. doi:10.18429/JACoW-LINAC2018-FR2A02

[2] I. Bylinskii, *et al.*, "AN ELECTRON LINAC PHOTO-FISSION DRIVER FOR THE RARE ISOTOPE PROGRAM AT TRIUMF", *in Proc. of PAC09*, Vancouver, BC, Canada, 2009, pp. 1958-1960. paper:WE4PBC04

[3] G. Ciovati, *et al.,* "Design of a cw, low-energy, high-power superconducting linac for environmental applications", *Physical Review Accelerators and Beams* 21, 091601 (2018), doi: 10.1103/PhysRevAccelBeams.21.091601.

[4] V. Ptitsyn, *et al.*, "HIGH LUMINOSITY ELECTRON-HADRON COLLIDER ERHIC", *in Proc. of IPAC2011*, San Sebastián, Spain, pp. 3726-3728. paper: TUOAN2

[5] J. Kewisch *et al.*, "ERL FOR LOW ENERGY ELECTRON COOLING AT RHIC (LERC)", *in Proc. of ERL2015*, Stony Brook, NY, USA, pp.67-71. doi:10.18429/JACoW-ERL2015-WEICLH1058

[6] Triveni Rao and David H. Dowell, "AN ENGINEERING GUIDE TO PHOTOINJECTORS", 2013, https://arxiv.org/abs/1403.7539.

[7] X. Chen, "A Plan for Electron Ion Collider in China". Proceedings of science, https://arxiv.org/pdf/1809.00448.pdf.

[8] R.J. Bakker *et al.*, "1 GHz modulation of a high-current electron gun", *Nuclear Instruments and Methods in Physics Research A* 307 (1991) 543-552. doi:10.1016/0168-9002(91)90229-J

[9] S. Koscielniak *et al.*, "PROPOSAL FOR A ½ MW ELECTRON LINAC FOR RARE ISOTOPE AND MATERIALS SCIENCE", *in Proc. of EPAC08*, Genoa, Italy TUOCG03, pp. 985-987.

[10] A. Todd *et al.*, "HIGH-PERFORMANCE ACCELERATORS FOR FREE-ELECTRON LASER (FEL) AND SECURITY APPLICATIONS", *in Proc. of PAC2011*, New York, NY, USA, pp. 2196-2198 paper:THP034

[11] H. P. Bluem *et al.*, "HIGH BRIGHTNESS THERMIONIC ELECTRON GUN PERFORMANCE", *in Proc. of ERL2011*, Tsukuba, Japan, pp. 34-39. Paper:WG1010

[12] Vadim Jabotinski, Yaroslav Derbenev and Philippe Piot, "Thermionic Bunched Electron Sources for High-Energy Electron Cooling", MEIC Collaboration Meeting SPRING 2016, Jefferson Lab, March 29-31, 2016.

[13] F. Ames *et al.*, "OPERATION OF AN RF MODULATED ELECTRON SOURCE AT TRIUMF", in Proc. of IPAC2018, Vancouver, BC, Canada, pp. 4705-4707. doi:10.18429/JACoW-IPAC2018-THPML025.

[14] Wieland Schöllkopf, *et al.*, "The new IR and THz FEL facility at the Fritz Haber Institute in Berlin", http://fel.fhi-berlin.mpg.de/uploads/2015_SPIE_95121L.pdf .

[15] Phillip Sprangle *et al.*, "High average current electron guns for high-power free electron lasers", *Physical Review Special Topics - Accelerators and Beams* 14, 020702 (2011).

[16] Superfish (SF), https://laacg.lanl.gov/laacg/services/download_sf.phtml

[17] General Particle Tracking (GPT), http://www.pulsar.nl/index.htm

[18] http://hiaf.impcas.ac.cn/

[19] C. K. Sinclair, *et al.*, "Development of a high average current polarized electron source with long cathode operational lifetime", *Phys. Rev. STAB,* Vol.10, 023501 (2007). doi: 10.1103/PhysRevSTAB.10.023501

[20] Wei Liu, "Study of Advanced Photocathodes for Highly Polarized Electron Sources". doctor thesis (in Chinese), 2017.

[21] D Angal-Kalinin, *et al.*, "PERLE. Powerful energy recovery linac for experiments. Conceptual design report", *Journal of Physics G: Nuclear and Particle Physics* 45 (2018) 065003 (71pp). doi:10.1088/1361-6471/aaa171

[22] R. Xiang, *et al.*, "LOW EMITTANCE POLARIZED ELECTRON SOURCE BASED ON SUPERCONDUCTING RF GUN", *in Proc. of SRF2007*, Peking Univ., Beijing, China, TUP66, pp. 293-295.

[23] Ben Hounsell, "Design of the PERLE injector", LHeC/FCC-eh workshop, 27/06/2018-29/06/2018.

[24] Adam Bartnik, *et al.*, "Operational experience with nanocoulomb bunch charges in the Cornell photoinjector", *PHYSICAL REVIEW SPECIAL TOPICS—ACCELERATORS AND BEAMS* 18, 083401 (2015). doi:10.1103/PhysRevSTAB.18.083401

[25] T. Xin, *et al.*, "Design of a high-bunch-charge 112-MHz superconducting RF photoemission electron source", *Rev Sci Instrum* 87, 093303 (2016); doi:10.1063/1.4962682.

[26] Vladimir N Litvinenko, *et al.*, "Commissioning of CW FEL Amplifier for Coherent Electron Cooler (CeC)", https://fel2019.vrws.de/talks/moa06_talk.pdf.

[27] Martin A. H. Schmeißer *et al.*, "Towards the operation of Cs-K-Sb photocathodes in superconducting rf photoinjectors", *PHYSICAL REVIEW ACCELERATORS AND BEAMS* 21, 113401 (2018). doi:10.1103/PhysRevAccelBeams.21.113401

[28] W. Liu, e*t al.*, "Record-level quantum efficiency from a high polarization strained GaAs/GaAsP superlattice photocathode with distributed Bragg reflector", *Appl. Phys. Lett.* 109, 252104 (2016). doi:10.1063/1.4972180