ELECTRON SOURCES AND POLARIZATION

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Abstract

In this presentation the present electron sources and the relevant issues will be discussed. For the electron positron colliders and accelerator based light sources, the electron gun and injector design, are arguably the most critical part. There are a variety of electron source designs: DC guns, normal-conducting RF guns, superconducting RF gun and hybrid guns. All variants have their own advantages and difficulties. We will overview the typical sources around the world, and compare their advantages and main challenges. The polarization production will also be discussed.

INTRODUCTION

For most of the electron accelerator facilities, design of electron gun and injector is arguably the most critical work. The quality of guns determines the ultimate performance of whole machine: current, bunch charge, bunch structure, repetition rate, transverse and longitudinal emittance. Certain applications require polarized electron beams. These parameters can only be degraded in subsequent beam line, will never become better [1].

High brillant beams are required by electron based colliders and high energy free electron lasers (FELs) [2]. Obviously, higher bunch charge in smaller transverse phase space and in smaller longitudinal phase space leads to higher brilliance. This gun must not work in continuous wave mode (CW), but provide very high electrical field at emission to overcome the space charge effect in the low energy stage.

Energy Recovery Linac (ERL), high power FELs and some other accelerator-based facilities place extra emphasis on high average current and low emittance, which needs robust cathodes with high emission efficiency, and high acceleration field in CW or high duty factor pulsed mode [1].

For microscopes and some accelerator applications, cold beams with extremely low emittance are request. Thermal emittance of the emitted electrons determines the limit of the lowest emittance of the beam. During the acceleration and transportation the emittance can only be degraded. So it is important to modify the cathode emission process and to optimize the accelerating structure to maintain the low emittance in the electron source [3].

Polarized beams are required by some high energy particle physics experiments, thus the spin-polarized electron sources are specially stimulated by the application of e+ e- colliders and electron-hadron colliders. For this case cathode materials with high spin-polarization rate and the good operation vacuum are the essential issue [4].

The main challenges of electron sources are to provide high efficient emitters, to deal with severe space charge effect and normally to work in the limited space. Although different facilities have their own focus, stability and reliability are the common requirement to ensure the routine operation, and also low dark current is request to reduce the damage risk and radiation doses for the downstream beam line.

EMITTERS

According to the different electron emitters, electron sources can be classified as thermal emission sources, photoemission sources, field emission sources and hybrid sources.

Thermionic cathodes, like Hexaborides, will emit when the temperature reach the threshold, when thermalized electrons can overcome the work function and finally escape the cathode surface [5]. Because of the high working temperature (for example 2500 K for LaB_6), thermal emitters can only work in direct current (DC) guns and in normal conducting radio frequency (NC RF) guns. With high electric fields, they are able to produce high current, but the time structure of bunches cannot be as short as those from photo-emitters and the emittance will be high due to the thermal emission process.

Photo-induced emission is up to now the best candidate for low emittance sources. Photocathodes can locate in DC guns, NC RF guns and lately in Superconducting RF guns (SRF guns). Photo-guns have produced beams with sufficient quality for many accelerator facilities [6]. But the critical gun vacuum and the expensive drive lasers increase greatly machine cost. In the next section the photo emission sources will be discussed.

Electron sources with cold field emission cathodes, like diamond field emitter and multiwall carbon nanotubes, are very common used in the field of electron microscopy, Gabor holography and also the accelerator facilities [7]. Due to the Fowler-Nordheim theory, the high fields built at the tips of emitter surface will induce stable field emission [8]. There are some new ideas inspired from field emission, for example, photo-induced field emission cathode or field enhanced photocathode [9], thermal field emission cathode [10], Schottky emission cathode [11], combining two emission models by using one method to reduce the work function of material and then extract the electrons with another method.

AVAILABLE ELECTRON SOURCES

Photoemission based electron sources (photo guns) have reached the best beam quality. For electron positron colliders, photo guns have the biggest potential to produce high current and low emittance beam. In this section we will overview the various on-going photo gun types, DC guns, NC RF guns and SRF gun projects.

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ISBN 978-3-95450-187-8

DC Guns

This type of sources consists of a photocathode, an anode and a high voltage between cathode and anode. DC guns are mature technique and have been used in many research accelerators since 1977, for instance, at Cornell [12], JAEA[13], KEK[14], Jlab [15], Daresbury [16] and so on. The state-of-art DC guns with negative electron affinity (NEA) cathodes deliver ~10 mA average current and hundreds of Coulombs from one single activated cathode [12].

Besides the mature technology, the main advantages of the DC guns include high average current, good vacuum 10-11 mbar for sensitive high QE photocathodes and arbitrarily high repetition rates. But the major challenges are obvious also: the limitation of the field on cathode surface, ion back bombardment limiting the cathode lifetime, dark current and space charge effect. The voltage between the cathode and anode are normally 300 - 500 kV, and very high voltage (500-750kV) is still essentially difficult.

As an example, Fig.1 shows the DC gun developed by JAEA and then operated and modified at KEK for ERL. In this design, chemically polished titanium is used for gun chamber and electrodes, and totally 14, 000 l/s NEG pumps are equipped in the vacuum chamber. This gun has been successfully operated at 500 kV for more than 8 hours without voltage breakdown [17].

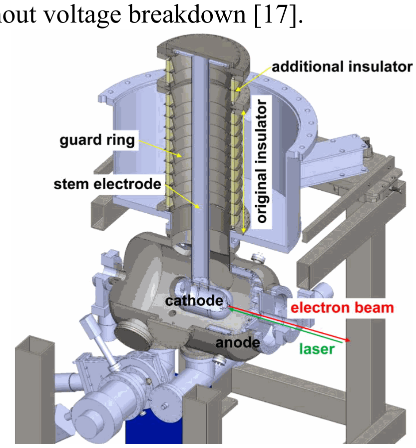

Figure 1: 500 kV DC gun at KEK. [17]

Normal Conducting RF Guns

There are two types of normal conducting RF guns: the first type is high frequency guns in L-band, S-band and even X-band and the other is low frequency guns in VHF or UHF range for potential CW operation.

NC RF guns with high frequency resonant cavities are successfully operated at CERN [18], FLASH [19], LCLS [20], etc. This is a mature technique producing the highest gradient (>100 MV/m) on cathode and the highest brilliance beam in pulsed mode. Also the application of a solenoid around the gun cavity makes the emittance compensation possible. The main limitations are bad vacuum during operation and low repetition rate. Also due to impedance and ohmic losses on the cavity wall, water cooling system is very demanding for the stable operation. High dark current from field emission is another problem for the beam application. The typical vacuum of 10^{-9} mbar restricts the choice of photocathodes. Only very robust cathode materials like Cu, Mg, Cs_2Te can be used. Sensitive NEA photocathodes and Cs_2KSb photocathodes are not suitable for RF guns at normal temperature. The dark current is another limiting factor in the RF guns operation at high accelerating gradients [21].

DESY RF gun is a very successful design. Fig. 2 shows the cross-sectional view of this gun. The operation gradient is up to 60 MV/m producing high brightness beams with 1 nC electron bunch and transverse normalized rms emittance as low as 1.26±0.13 mm mrad [22].

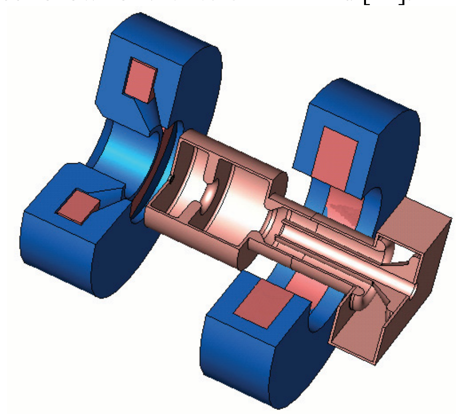

Figure 2: The transverse cross-sectional view of DESY normal conducting RF gun [23]. The 1.6 cell copper cavity produces 60 MV/m at emission.

The other type of NC RF guns are low frequency guns for CW mode operation. Good examples are LBNL 186 MHz gun [24], LANL/AES 700 MHz gun [25] and Boeing 433 MHz RF gun. Boeing RF gun has reached duty factor of 25 % and produced 32 mA average current with a K_2CsSb photocathode driven by 532 nm green laser [26].

Figure 3 is the cross view of the APEX RF gun developed at LBNL. The 186 MHz RF field provides a gradient on cathode of 20 MV/m in 4 cm gap. With Cs_2Te photocathode it succeeded to produce 0.3 mA average current in 1 MHz repetition rate [27].

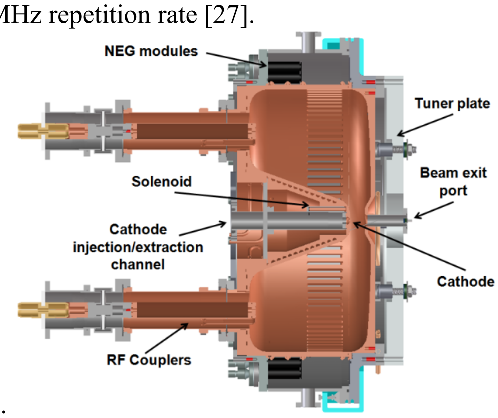

Figure 3: The cross-section view of the APEX RF gun developed at LBNL [27]. The 186 MHz RF field provides a gradient on cathode of 20 MV/m, and the powerful pumps around the cavity maintain good vacuum for alkali photocathodes.

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Superconducting RF Guns

There are several ongoing and proposed accelerator projects using SRF guns. The advantages of SRF guns are the high bunch repetition rate, high fields (>20 MV/m) on cathode surface and excellent vacuum environment for the sensitive cathode materials. SRF guns are suitable for CW operation with medium bunch charge (hundreds of pC). But the sensitivity of the superconducting cavity and the compatibility of the cavity and high QE photocathodes are the major challenges for this type sources in the practical operation. On the other hand, how to reduce the dark current from the field emission is also a question. According to the combination methods of RF fields and photocathodes there are four types of SRF guns.

Elliptical cavity + NC cathode is a classic design. The elliptical cavity is based on TESLA technology, able to build high field at emission up to 40 MV/m, which can compare favorably with NC RF guns. Since 1998 HZDR has been devoting to two generations of 3+1/2 cell SRF guns [28]. And since 2008 HZB is working on a 1.4 cell SRF gun for 100 mA high current for the ERL project [29]. Recently KEK tested a 1+1/2 cell SC cavity for the SRF gun prototype, which has a feature: the excitation laser injects from backside of the photocathode. These cavities have resonant frequency of 1.3 GHz. There is also design with low frequency elliptical cavity. The cavity of the BNL/AES SRF gun is 703.75 MHz. Cylindrical protrusions on the outside of the cavity's back wall and on the cathode stalk form a folded RF choke joint with four gaps, where unexpected multipacting appeared during operation. This gun has generated the first beams from CsK_2Sb photocathodes [30].

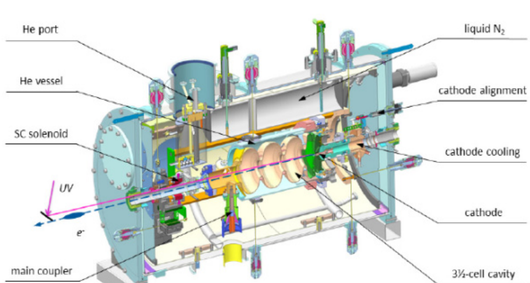

Figure 4: SRF gun-II cryomodule at HZDR. Normal conducting photocathode is inserted into the SC elliptical cavity. A SC solenoid is installed in the cryomodule for emittance compensation.

As an example, Fig. 4 shows the SRF gun II developed by HZDR [31]. The normal conducting photocathode is cooled with liquid nitrogen, surrounded by a SC cavity as RF choke filter. Between the 3+1/2 cell Nb cavity and the NC photocathode there is a vacuum gap to isolate the cathode to SC cavity. The cathode structure allows to load a DC voltage to suppress the possible multipacting. Copper, Magnesium and Cs_2Te can be used as photo emitter driven by a UV laser. A SC solenoid is installed in the gun cryomodule, used to compensate the transverse emittance [32]. Due to the strong field emission led by the contamination during the cathode exchange, the field was restricted to 7 MV/m. However it should be still able to generate a bunch charge up to 500 pC.

Quarter wave resonator + NC cathode is another variant. The advantages of the quarter wave resonator (QWR) are low RF losses, small HOM effect, long bunch allowed due to the relative constant field in the acceleration gap.

The 200MHz QWR SRF gun built in University of Wisconsin-Madison has achieved 20 MV/m in CW operation with the cathode inserted. Bunch charges of ~100 pC have been delivered [33]. As the second example, the Naval Postgraduate School (NPS) has built a 500 MHz QWR SRF gun as electron beam source, which has a photocathode with adjustable position and uses a unique cascaded RF coupler design [34].

In 2014 a 112-MHz superconducting QWR electron-gun cryomodule was developed in a collaboration between BNL and Niowave, Inc. as part of testing the concept of coherent electron cooling. The gun is designed to deliver electrons with a kinetic energy of 2 MeV. Fig. 5 shows the layout of the 112 MHz gun, recently generating 3 nC bunches at 1.7 MeV from an CsK_2Sb driven by a green laser of 532 nm [35].

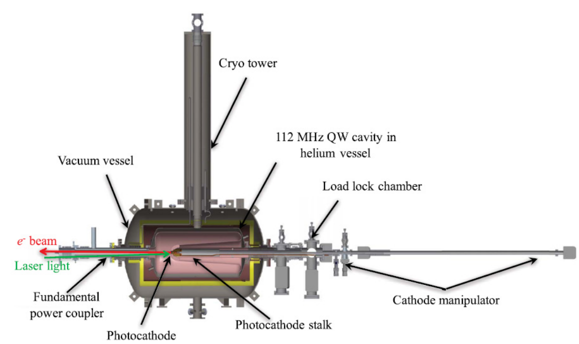

Figure 5: Cross section of the 112 MHz SRF gun (elevation view) at BNL [35].

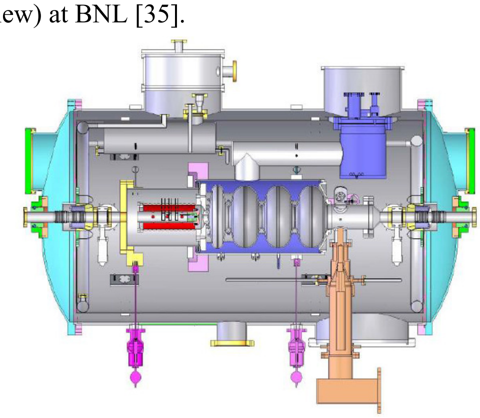

Figure 6: the cross section of PKU DC-SRF gun [36].

Elliptical cavity + DC pierce + NC cathode is a kind of hybrid gun, combining low voltage DC gun and SRF gun. Peking University has successfully developed the DC-SRF gun consisting of a nominal 45 kV DC Pierce gun and a 1.3GHz 3.5 cell superconducting RF cavity.

ISBN 978-3-95450-187-8

The normal conducting Cs_2Te cathode is installed in the DC pierce structure. Extracted electrons are accelerated in DC field, and then float through a centimeters gap into RF field, so the danger of contamination due to cathode exchange is reduced. However, because of the low field on cathode and the floating gap, the bunch charge and the transverse emittance are strictly limited (Fig. 6). E_{acc} of the gun reached 8.5 MV/m, and produced electron beam of 1mA at 81.25 MHz with normalized transverse emittance 2.0 mm-mrad [36].

All SC gun can avoid the compatibility problem of the NC cathode and SC cavity, and reduce the contamination risk for the SC cavity. The development of the SC gun is an on-going R&D program at DESY since 2006. Recently, the 1.6-cell niobium cavity was tested in a vertical cryostat with exchangeable plug, reaching 63 MV/m with Nb-plug and 32 MV/m with Pb-coated plug. The limitation of this SC gun is the bunch charge because of the very low QE of superconducting photocathodes [37].

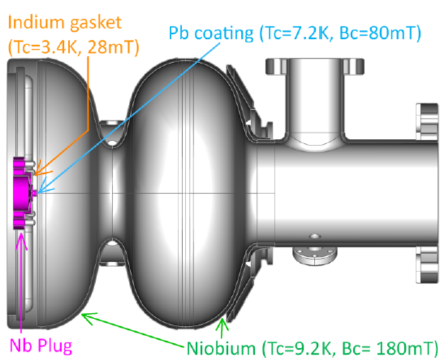

Figure 7: Design concept of the SC gun at DESY [37].

POLARIZED ELECTRON SOURCES

Polarized beams play a crucial role in the experimental programs of RHIC (Relativistic Heavy Ion Colliders), HERA (Hadron-Elektron-Ring-Anlage), as well as in the e+e- collider program.

In 1970s, there are several early polarized electron sources for accelerators: Yale / Stanford source based on the photoionization of 6Li atoms, the source for Bonn synchrotron based on Fano effect, and Bielefeld source based on field emission from W-EuS. Aftter 1974, benefit from the contribution of material scientists, GaAs(Cs) photocathodes illuminated with circularly polarized light become the most popular method to produce polarized electron beam for accelerators [38]. This method keeps state-of-art with DC guns [39]. Moortgat-Pick and the co-authors have introduced the polarized electron sources and positron sources in detail in reference [40].

As for the gun construction, the only special requirement is the extremely high vacuum (XHV) during the operation. Thus the polarized electron sources presently in operation are based on DC guns with semiconductor photocathodes. There is argument to use RF guns (SRF gun or RF gun in cryogenic temperature) with GaAs-based photocathodes for polarized electron guns [41]. However, up to now no successful operation has been reported.

The most important element for polarized electron sources is polarized photocathodes. The bulk-GaAs crystal can reach polarization up to 50% with high QE. The QE is mainly determined by the property of the NEA surface. It is realized by using a combination of two techniques; band-bending due to the heavily p-doped surface layer, and the monolayer formation of alkali (e.g. Cs) and oxidant (O) on the semiconductor surface [42].

Higher polarization is an ongoing R&D aim. Researchers at several laboratories, including Nagoya University and KEK[43], St. Petersburg Technical University [39], and ISP Novosibirsk [44] etc. have been searching for a cathode structure that would yield electron beams with a higher polarization while maintaining a high QE. The strained layer InGaP- or GaAsP-cathodes can reach polarization of 70-80% and QE of 0.1-0.4%. Today the most promising photocathode structure is the superlattice with strain pioneered by the Nagoya-KEK collaboration [42] and St Petersburg [39] . The maximal polarization of 92 % with quantum efficiency of 0.85 % at room temperature has been reported in St Petersburg with superlattices with strained QW AlInGaAs/AlGaAs, shown in Fig. 8.

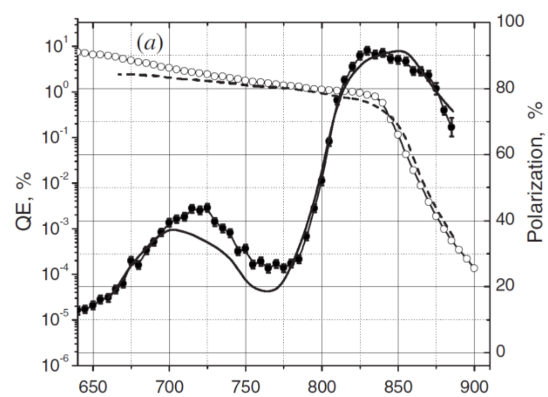

Figure 8: Polarization (solid symbols) and quantum efficiency (circle symbols) spectra of the emitted photoelectrons from a strained AlInGaAs/AlGaAs superlattice sample [39].

The main challenges for polarized sources come from the photocathodes. The short life time due to harmful rest gases and ion back bombardment during the operation in DC field. At JLab, ion back bombardment is the predominant mechanism limiting the operational lifetime of the cathodes during electron emission [45]. Note to this point, in RF field there is no reported problem of ion back bombardment to photocathodes.

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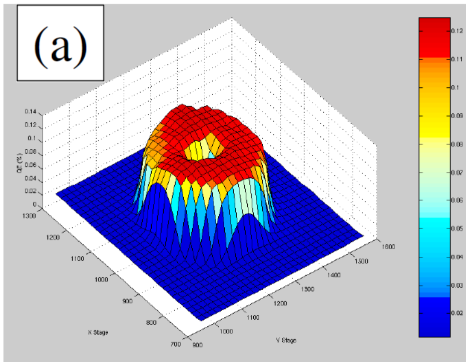

Figure 9: QE scan of a photocathode obtained over many weeks of continuous operation. The pattern of QE degradation indicates damage from ion back bombardment [45].

Another problem faced by polatized electron sources is the response time of GaAs-based photocathodes slower than that of metallic and alkali cathodes. For bulk GaAs, the response time is measured as 1.8 ps with 400nm and 2.8ps with 800nm [46] (shown in Fig. 10). Response time of semiconductor AlInGaAs/AlGaAs superlattices was reported also in level of several picoseconds [47]. Compared with sub-ps response time of metal and alkali photocathode, GaAs produce a tail of bunches or longitudinal halo.

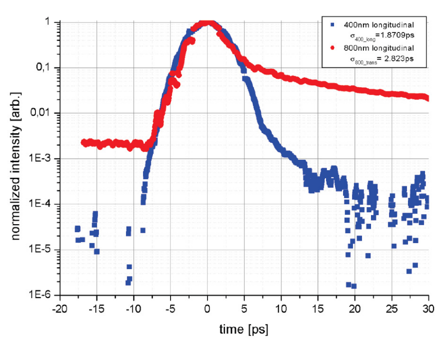

Figure 10: The response time of NEA GaAs photocathode measured in Mainz [46].

CONCLUSION

Many groups around the world are intensively working on different schemes and technologies potential for achieving the required electron beams: bunch charge density, brilliance, average current, bunch structure, repetition rate, transverse and longitudinal emittance and polarization. Gun structure design has to promise high field for acceleration and good gun lifetime. Suitable electron emitters have to be chosen to fulfil the requirements of endurance in high field, low thermal emittance, prompt response time and high polarization for colliders and certain applications.

- choose appropriate emitter for more electrons
- build high field for acceleration for better beam quality
- build an accurate diagnostic beam line

Attention must be paid also on the study of beam dynamics in the gun and injector, where electron beams have only low energy and suffer strong space charge effect. Modeling and computational issues are greatly important for conceptual design. A number of simulation codes, EGUN, ASTRA, PARMELA…can help to optimize the field. Careful simulation is needed for emittance compensation and nonlinear effect in the high density bunches.

ACKNOWLEDGEMENT

The work is supported by the European Community under the FP7 programme (EuCARD-2, contract number 312453, and LA3NET, contract number 289191) and by the German Federal Ministry of Education and Research (BMBF) grant 05K12CR1.

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ISBN 978-3-95450-187-8