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OVERVIEW OF CW RF GUNS FOR SHORT WAVELENGTH FELs

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Abstract

Hard X-ray FELs (XFELs) operating with pulsed RF provides unprecedented peak brilliance for scientific research. Operating the accelerators with CW RF improves the flexibility w.r.t. the available time structure for experiments and opens the next frontier of average brilliance. One of the challenges of CW XFELs is the electron source, which requires both the CW operation and the highest possible beam quality allowing lasing at shortest wavelengths. With a given linac energy, higher beam brightness results in shorter X-ray wavelength. As the injector defines the lower limit of the electron beam brightness of the complete accelerator, R&D is devoted to CW photoinjector improvements since decades. In this contribution, the worldwide development status of CW RF guns, both normal conducting and superconducting, is reviewed.

INTRODUCTION

Short wavelength free electron lasers (FEL) in the X-ray regime have seen great success in the last decades, such as FLASH, LCLS, the European XFEL and so on [1–3]. These X-ray FEL light sources provide much shorter (sub 100 fs) and much brighter pulses than storage rings [4]. Current X-ray FEL facilities are based on pulsed RF linacs with duty factors lower than 1%, which reduces the average electron beam pulse rate (<27000/second) and thus the average X-ray brightness. Operating the superconducting (SC) linacs in CW mode enables both higher average brightness and more flexible timing patterns for X-rays. Two CW X-ray FELs are under construction, one is LCLS-II in the US, and the other is SHINE in China [5,6]. Compared to the pulsed X-ray FEL, the linac energy of CW X-ray FEL is roughly a factor of 2 lower. According to LCLS-II high energy upgrade (LCLS-II-HE) studies, an even brighter electron source (0.1 µm at 100 pC) is needed to extend the lasing energy from 13 keV to 20 keV [7].

Due to the common needs of high brightness CW injectors, both the energy recovery linac (ERL) community and the FEL community are pushing the R&Ds of CW guns. The ERL guns focuse more on high average current (~100 mA), while the FEL guns focuse more on low emittance beams. Both communities emphasize the developments of high QE cathodes and high gradient guns. R&D is performed on DC guns, normal conducting (NC) RF guns, SC RF gun and hybrid guns [8–11]. Due to the relatively low cathode gradient (<5 MV/m) and low gun voltage (<500 kV), DC guns are mainly developed for the ERL applications to achieve a high average current. The Cornell DC gun also demonstrated the baseline emittance required by LCLS-II, but the linac bunch compression is compromized according to LCLS-II studies [12, 13]. Therefore in this paper, overview on CW guns is focused on photocathode RF guns for applications in short wavelength FELs.

HIGH BRIGHTNESS INJECTORS FOR FELs

There are two types of photoinjectors for X-ray FELs, one is based on a high gradient RF gun, and the other is based on a medium to low gradient gun. A high gradient gun enables photoemission of both high peak current and low thermal emittance, i.e. 'pancake' emission, and the beam is then matched into a booster linac by a gun solenoid for emittance compensation. This type of injector uses high frequency (>1 GHz) pulsed NC guns, and the emission gradient is about 40 to 60 MV/m, which is roughly 50% to 70% of the peak cathode field due to the phase slippage. Such pulsed gun performances cannot be scaled to the CW mode for NC guns due to a few megawatt average RF heating. SC CW guns have the potential to reach similar fields. SC L-band guns are under development at HZDR, HZB, DESY, KEK and PKU. VHF-band quarter wave resonator (QWR) guns are under development at BNL and Wisconsin/SLAC/ANL.

To reach similarly low emittance as achieved in high gradient guns, photoemission in medium to low gradient guns has to start with a longer laser pulse to keep the low thermal emittance, i.e. 'cigar' emission. The long beam is compressed by a buncher cavity following the gun to restore the high peak current, and then matched into the booster linac by solenoid focusing for emittance compensation. To host the long beam, the gun cavity should be low frequency, which makes the beam dynamics like DC gun. The phase slippage is negligible in the low frequency gun, hence the emission field is almost equal to the peak cathode field. This type of injector was originally optimized for a DC gun based ERL injector, and was later adapted for the VHF-band NC CW gun developped at LBNL. The NC VHF gun is also under study at SLAC, DESY and SHINE.

APEX Gun and APEX2 Gun at LBNL

Inspired by the Cornell DC gun, a VHF band (185.7 MHz) gun was developed at the Advanced Photoinjector EXperiment (APEX) for CW soft X-ray FEL project NGLS. The low frequency and large cavity is good for both the cavity cooling and the vacuum. The reentrant cavity shape not only enhances the cathode field and shunt impedance, but also makes the cavity size compact as compared to a pillbox cavity. The APEX gun concept was demonstrated in three phases. In phase 0, the designed CW RF power and ultra high vacuum was demonstrated [14]. In phase I, the

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gun demonstrated compatibility with the high QE Cs_2Te cathode and a 300 µA average current with 1 MHz beam repetition rate [15]. In phase II, the 20 pC beam brightness was demonstrated for LCLS-II [16].

In 2016, LBNL colleagues started to design the AEPX2 gun, which aims to increase the beam brightness at least by a factor of 4 for both LCLS-II-HE and ultrafast electron diffraction and microscopy [17]. To reduce the RF heating, the gun frequency is lowered to 162.5 MHz. The APEX2 gun is a two cell design. The first cell is designed for a higher cathode field above 30 MV/m, and the second cell is for boosting the beam energy above 1 MeV. Simulations show the APEX2 gun can reach 0.1 µm emittance for 100 pC beam with a 0.6 µm/mm thermal emittance [18].

The main parameters of the APEX gun and APEX2 gun are summarized in Table 1 together with the other CW normal conducting RF guns.

LCLS-II Gun at SLAC

Simulations show the LCLS-II photoinjector based on the APEX gun meets the baseline requirements [19]. A slightly modified APEX gun is produced for LCLS-II by LBNL. The LCLS-II gun commissioning is ongoing and full RF power is already achieved [20]. Next, they are going to exchange the Mo cathode by the Cs_2Te cathode for 1 MHz beam operation and electron beam optimization.

CW VHF Gun Design for SHINE

SHINE decided to use the VHF gun as the baseline CW gun technology [21]. The SHINE VHF gun frequency is 162.5 MHz with an operation range between 750 kV and 1 MV, corresponding to a RF power of 70 kW and 120 kW respectively. The cathode field reaches 30 MV/m at 1 MV. The prototype gun is now under engineering design and will be produced soon.

DESY – CW Gun for European XFEL

A future upgrade of the European XFEL (EXEL) foresees an additional CW operation mode, which will increase the flexibility in the photon beam time structure [22–25]. One of the challenges of this operation mode is a CW operating photoinjector. For more than a decade DESY, in collaboration with TJNAF, NCBJ, BNL, HZB and HZDR, has performed R&D to develop an all SC RF gun with a lead cathode screwed in a clean room into a hole on the backside of a 1.6 cell L-band cavity [26]. The cavity can be cleaned after the cathode insertion, and possibly lost cathode particles should not heat and quench the cavity, as they are all superconducting. In contrast to setups with cathode loadlock systems, exchanging cathodes requires a complete disassembly of the cryostat and bringing the gun cavity back into the cleanroom. The target parameters of the DESY SC gun can be found in Table 2 together with the other L-band SC guns.

In parallel to the SC gun program, a backup option following the NC VHF gun approach is under physics design study [27]. The DESY VHF gun is a 216.7 MHz single cell gun with both higher gradient (28 MV/m) and higher voltage (830 kV) than APEX gun. The higher gun frequency reduces the RF breakdown risk and better fits the Eu-XFEL timing system. The acceleration gap is reduced compared to the APEX gun to increase the cathode field and consequently the beam brightness. A 400 kV buncher is also under design to match the higher gun voltage [28].

HZDR – SRF Gun for ELBE (THz FEL)

In the nineties HZDR started the construction of the compact SC L-band linac ELBE as source of different secondary beams which started operation in 2001 [29, 30]. The initial and main injector of ELBE is a thermionic gun. In parallel to the commissioning of the facility R&D for a SC photoinjector started [31]. It includes a 3.5 cell L-band cavity with chock cell and a SC solenoid in a cryostat, and a loadlock system for cathode exchange. The Cs_2Te cathode was successfully tested in the first gun, but has some overheating issues in the second gun [32]. Since 2017, the SC gun started user operations for terahertz beamline with a Mg cathode [33]. Currently, the gun R&D is focused on establishing a Cs_2Te cathode for user operaiton and a dedicated gun-lab.

HZB – SRF Gun for bERLinPro

BERLinPro is an accelerator facility under development and construction at HZB since 2011 to demonstrate the principle of an energy recovery linac [34, 35]. The first two generations of 1.3 GHz SC guns were tested with SC lead cathode, and a 20 to 30 MV/m peak acceleraiton gradient was achieved. To achieve the 100 mA average current, the third generation SC gun was designed for a NC high QE CsK_2Sb cathode, including a 1.4 cell cavity with choke cell, a cathode loadlock system and a SC solenoid [36]. In 2011 a first full setup of this injector was tested in the HoBiCaT facility [37]. In 2017 a beam test was performed with a copper cathode. After exchaning the cathode, high field emission was observed limiting the gun performance [38]. The current focus of the R&D work lies on the cathode exchange system to achieve higher gradients with a CsK_2Sb cathode. It is foreseen to move the photoinjector test setup from the HoBiCaT facility to the bERLinPro accelerator hall [39].

KEK – SRF Gun for KEK-ERL

In 2008 the development of the key elements for the compact energy recovery linac (cERL) at KEK started [40]. In 2010 the construction started and in 2014 first beam was transported through the recirculation loop using an injector consisting of a 500 kV photocathode DC gun [41]. Using an SRF gun instead is expected to be advantageous w.r.t. higher bunch charges and low emittances. In 2013 KEK started to develop a 1.5 cell SC gun cavity with a choke cell and performed very successful vertical tests with a record high on axis peak field of about 57 MV/m [42]. In contrast to other SC gun setups the cathode will be illuminated by the cathode laser from the backside using a transparent superconductor as substrate for the CsK_2Sb cathode [43]. Currently the

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Table 1: Summary of Normal Conducting VHF Gun Performances

Parameter	**APEX**	**LCLS-II**	**APEX2**	**DESY**	**SHINE**	**Units**
Status	Routine operation	Beam test	Design	Design	Design	N/A
Frequency	185.7		162.5	216.7	162.5	MHz
Cathode field	19.5		34	28	23.5-31	MV/m
Gun voltage	750		1640	830	750-1000	kV
Average RF power	90		176	100	69-120	kW
Shunt impedance	6.3		15.2	6.9	8.2	Mohm
Peak surface field	24.1		37	30.6	28.4-37.5	MV/m
Peak power density	25		32	37	16.9-29.5	W/cm^2
Diameter/Length	69.4/35		78.6/74.7	68/26.8	80/42	cm
Beam parameter	Measurement	Simulation	Simulation	Simulation	Simulation	pC
Bunch charge	20-300	20-300	100	100	100	pC
Bunch rate	1	1	1	1	1	MHz
Dark current	0.1	<400	N/A	N/A	N/A	nA
Projected emittance	<0.2 (20 pC, 6 A)	0.2-0.6 (5-30 A)	0.08 (12 A)	0.2 (11 A)	N/A	µm.rad
Cathode	Cs_2Te (CsK_2Sb)	Cs_2Te	CsK_2Sb	N/A	N/A	N/A
Thermal emittance	0.75 (0.6)	N/A	0.6	1.0	N/A	µm.rad/mm
Cathode assembly	Loadlock, RF spring					N/A
Lifetime in operation	8 (2)	N/A	N/A	N/A	N/A	week
Private reference	F. Sannibale	F. Zhou	D. Li	H. Qian	Q. Gu	N/A

Table 2: Summary of L-band SC Gun Performances

Parameter	**HZDR**	**HZB**	**KEK**	**DESY**	**Units**
Status	R&D	Routine operation	R&D	R&D	N/A
Frequency	1300	1300	1300	1300	MHz
Cavity type	TESLA 3.5	TESLA 1.4	TESLA 1.5	TESLA 1.5	cell
Gun energy	3-4	2	>3	3-4	MeV
Peak axis field	20.5	7.5	31.5	40	MV/m
Cathode field	12	7.5	23	40	MV/m
Gradient limitation	Field emission	Field emission	N/A	N/A	N/A
Beam parameter	Measurement	Simulation	Simulation	Simulation	N/A
Bunch charge	200	77	80	100	pC
Bunch rate	0.1	1300	1300	0.1	MHz
Dark current	30	100	N/A	N/A	nA
Projected emittance	2-15	<0.5	0.6	N/A	µm.rad
Cathode	Mg (Cs_2Te)	Cu (CsK_2Sb)	CsK_2Sb	Pb	N/A
Cathode assembly	RF choke loadlock	RF choke loadlock	RF choke loadlock	Screw in	N/A
Cathode lifetime	50	N/A	N/A	N/A	week
Private reference	A. Arnold J. Teichert R. Xiang	T. Kamps A. Neumann	T. Konomi	E. Vogel	N/A

R&D focuse is on improving the cathode cooling and the preparation of a horizontal test.

PKU – DC-SRF Gun

Since 2000 work on SRF photo injectors is performed at Peking University [44]. Initially a SC 1.5 cell L-band cavity after a DC voltage gap for the initial acceleration of the photoelectrons has been used and replaced in 2014 by a 3.5 cell L-band cavity. The DC gap at the entrance of the SC cavity successfully avoided the complication of a NC cathode in the SC cavity, but it also limites the cathode gradient. Since 2014 the gun achieved routine operations with a Cs_2Te cathode. The injector is used for the provision of high repetition rate terahertz radiation and ultrafast electron

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Table 3: Summary of QWR SC Gun and Hybrid SC Gun Performances

Parameter	BNL	SLAC	PKU	Units
Status	Routine operation	R&D	Routine operation	N/A
Frequency	113	200	1300	MHz
Cavity type	QWR	QWR	TESLA 3.5 (1.5)	cell
Gun energy	1.25	1.1	3-4 (2.8)	MeV
Peak axis field	20	12	22 (26.6)	MV/m
Cathode field	10-20	12	2.6 (6)	MV/m
Gradient limitation	Field emission	N/A	DC	N/A
Beam parameter	Measurement	Measurement	Measurement (simulation)	N/A
Bunch charge	up to 10700	100	20-50 (100)	pC
Bunch rate	0.078	0.001	27 (1)	MHz
Dark current	1	N/A	1 (N/A)	nA
Projected emittance	0.15 (100 pC, <1 A)	1.5	1.5 (0.5-0.3)	µm.rad
Cathode	CsK_2Sb	Cu	Cs_2Te (CsK_2Sb)	N/A
Cathode assembly	RF choke loadlock	RF choke	Screw in loadlock	N/A
Cathode lifetime	4-8	N/A	4-8	week
Private reference	V. Litvinenko E. Wang Q. Wu T. Xin	B. Dunham X. Wang	S. Huang K. Liu	N/A

diffraction (UED) experiments [45]. The next generaiton DC-SRF gun is optimized for generating high brightness beams for a X-ray FEL with improvements on the cathode gradient and a smaller emittance [46,47]. The parameters of the existing 3.5 cell gun and the next generaiton 1.5 cell gun are summarized in Table 3.

BNL – SRF Gun for Cooling Hadrons

In 2001 first plans and proposals were made to add a high energy electron cooling to the Relativistic Heavy Ion Collider (RHIC) [48]. Since 2007 an FEL-based Coherent electron Cooling (CeC) system has been developed and studied [49]. The major installation of the CeC system occurred during RHIC shutdown in 2016 and is in routine operation since then [50]. The electrons are generated by a CW photoinjector using green laser light on a CsK_2Sb cathode. The gun consists of a SC 112 MHz quarter wave resonator (QWR) developed by BNL in collaboration with the company Niowave. The typical cathode lifetime for the high bunch charge (~nC) operation is one to two months and the cathodes can be exchanged via a load lock system [51]. The parameters of the BNL QWR gun are summarized in Table 3.

Wisconsin/SLAC/ANL - SRF Gun for LCLS-II HE & UED/UEM

The University of Wisconsin-Madison presented 2009 a pre-conceptual design for a seeded VUV/soft X-ray FEL, called WiFEL, serving multiple simultaneous users [52]. For the photoinjector a SC 200 MHz QWR gun has been selected, designed and constructed together with the company Niowave [53]. In 2013 first beam was generated and simple beam measurements were made [54]. Afterwards this photoinjector was transported to SLAC as a potential electron source for the LCLS-II-HE and for ultrafast electron microscopy (UED & UEM) experiments. Recommissioning at SLAC took place and first beam were generated in 2018 [55]. Due to the lack of a cryogenics plant for the operation, the R&D activities with this photoinjector will resume at Argonne National Laboratory (ANL) after its transfer from SLAC to ANL [56].

CW GUN VS PULSED GUN

CW RF gun technology is still far from mature, and the peak acceleration gradient of around 20 MV/m is still low w.r.t. the hard X-ray FEL lasing at the shortest wavelength. Besides a higher gun gradient, the beam transverse brightness can also be improved by low emittance cathodes, laser shaping and 'cigar' photoemission instead of 'pancake' photoemission in the low frequency CW guns [12,57].

Figure 1 is a 100 pC simulation example comparing the PITZ pulsed injector and the LCLS-II CW injector with a thermal emittance of 1 µm/mm. The LCLS-II injector based on the 20 MV/m APEX gun is almost identical to the 40 MV/m PITZ gun in terms of transverse emittance and RMS bunch length. When the beam peak current is around 10 A (RMS bunch length is between 1 mm and 1.3 mm), both the AEPX gun and PITZ gun can deliver the baseline

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emittance for LCLS-II. To reach 0.1 µm emittance for 100 pC, even the 60 MV/m PITZ gun needs a lower thermal emittance cathode.

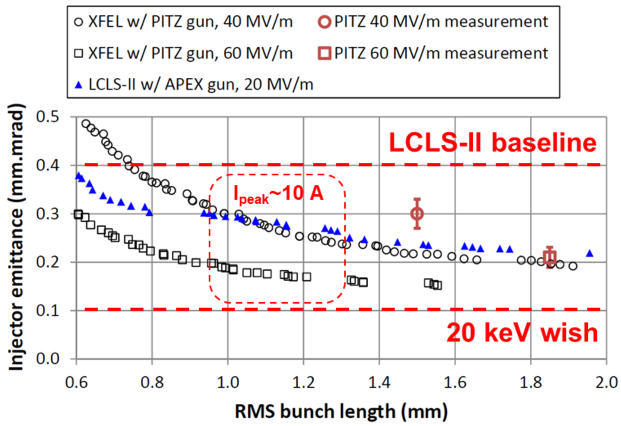

Figure 1: Simulation and experiment results between pulsed injector (PITZ) and CW injector (LCLS-II).

CHALLENGES AND LIMITATIONS FOR HIGH GRADIENT CW RF GUN

The next generation of CW guns aim for peak acceleration gradients higher than 20 MV/m. There are several challenging factors for higher gradient operating in CW. One is dark current and field emission, and the other one is the RF breakdown, both of which requires a better surface treatment of CW guns.

Based on the dark current versus gradient measurement from the APEX gun and the HZDR gun, extrapolations show the APEX gun will generate 400 nA dark current at a cathode field of 29 MV/m, and the present HZDR SC gun setup and the presently used cathode would generate more than 1 µA dark current at a peak acceleration field of 41 MV/m [58,59]. Both will go beyond the dark current specification of 400 nA set by LCLS-II project without dark current collimation.

In the framework of the TELSA technology collaboration SRF technology has been pushed from an average accelerating gradient of about 5 MV/m in the late 1980th to an average accelerating gradient well above 26 MV/m in operation at the Eu-XFEL. In vertical tests L-band SRF gun cavities showed similar high accelerating gradients corresponding to cathode fields of 40 MV/m to 60 MV/m demonstrating the potential of this technology. Nevertheless, the special geometry of the gun cavities, e.g. choke cell, cathode backplane and cathode insertion, as compared to the standard TESLA cavities requires R&D for the adaptation of all production and surface treatment steps to obtain the required smooth and ultra clean cavity surfaces. Dark current and field emission in SRF cavities is caused by contamination. The insertion of cathodes in this environment is a challenge, especially when the cathode materials are normal conducting. Furthermore, cathodes themselves may be the cause of dark current. The combination of the cathodes and the SRF gun cavities requires further R&D for higher gradients.

For reliable operation, CW normal conducting cavities are usually designed with a surface peak electric field below two times the Kilpatrick field to minimize the RF breakdown risk [60]. This corresponds to 27.2 to 30.4 MV/m for 162.5 MHz and 216.7 MHz respectively. The Kilpatrick criteria is only empirical, and is surpassed in most pulsed structures. Besides, the RF breakdown also depends on cavity material and surface treatment. The APEX gun was operated at 840 kV without breakdown, and the surface peak electric field corresponds to $1.9E_{kilp}$ [58]. Nevertheless, this may be a limiting factor for low freqency normal conducting guns to go to higher gradients.

SUMMARY AND OUTLOOK

A joint effort from the ERL and CW FEL community is pushing the frontier of high brightness CW RF guns. Although the R&D focus is different between the two communities, a lot of basic research are in common, such as the cavity surface treatment, the cathode, the injector optimization and so on. The LBNL type normal conducting VHF gun has demonstrated both RF and cathode performance for CW FEL operation, and the 20 pC beam brightness meets the LCLS-II specifications. Simulations show such a gun can meet the baseline requirement of LCLS-II from 20 pC to 300 pC, but the high charge beam brightness is still to be demonstrated by the LCLS-II team. CW SRF guns at HZDR, BNL and Peking University have achieved routine operation with peak acceleration gradients up to ~20 MV/m, and several new guns are under R&D at HZB, KEK, SLAC and DESY. Low emittance was measured for 500 pC beam with low peak current (<1 A) at BNL, and high peak gradient up to 60 MV/m was demonstrated in vertical tests at DESY and KEK. Although the current SC gun performance is still not ready for the CW hard X-ray FEL, intense R&D from many labs are pushing the technology to the next level.

REFERENCES

[1] W. Ackermann *et al.*, "Operation of a free-electron laser from the extreme ultraviolet to the water window", *Nature Photonics*, vol. 1, pp. 336–342, 2007. doi:10.1038/nphoton.2007.76

[2] P. Emma *et al.*, "First lasing and operation of an ångstrom-wavelength free-electron laser", *Nature Photonics*, vol. 4, pp. 641–647, 2010. doi:10.1038/nphoton.2010.176

[3] H. Weise and W. Decking, "Commissioning and First Lasing of the European XFEL", in *Proc. FEL'17*, Santa Fe, NM, USA, Aug. 2017, pp. 9–13. doi:10.18429/JACoW-FEL2017-MOC03

[4] Z. Huang, "Brightness and Coherence of Synchrotron Radiation and FELs", in *Proc. IPAC'13*, Shanghai, China, May 2013, paper MOYCB101, pp. 16–20.

[5] J. N. Galayda, "The LCLS-II: A High Power Upgrade to the LCLS", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 18–23. doi:10.18429/JACoW-IPAC2018-MOYGB2

[6] Z. Zhu, Z. T. Zhao, D. Wang, Z. H. Yang, and L. Yin, "SCLF: An 8-GeV CW SCRF Linac-Based X-Ray FEL Facility in Shanghai", in *Proc. FEL'17*, Santa Fe, NM, USA, Aug. 2017, pp. 182–184. doi:10.18429/JACoW-FEL2017-MOP055

[7] T. O. Raubenheimer, "The LCLS-II-HE, A High Energy Upgrade of the LCLS-II", in *Proc. FLS'18*, Shanghai, China, Mar. 2018, pp. 6–11. doi:10.18429/JACoW-FLS2018-MOP1WA02

[8] A. Arnold and J. Teichert, "Overview on superconducting photoinjectors", *Phys. Rev. ST Accel. Beams*, vol. 14, p. 024801, 2011. doi:10.1103/PhysRevSTAB.14.024801

[9] J. K. Sekutowicz, "SRF Gun Development Overview", in *Proc. SRF'15*, Whistler, Canada, Sep. 2015, paper THAA02, pp. 994–1000. doi:10.18429/JACoW-SRF2015-THAA02

[10] F. Sannibale, "Overview of Electron Source Development for High Repetition Rate FEL Facilities", in *Proc. NAPAC'16*, Chicago, IL, USA, Oct. 2016, pp. 445–449. doi:10.18429/JACoW-NAPAC2016-TUB3IO02

[11] V. Volkov *et al.*, "Latest Results of CW 100 mA Electron RF Gun for Novosibirsk ERL Based FEL", in *Proc. LINAC'18*, Beijing, China, Sep. 2018, pp. 598–600. doi:10.18429/JACoW-LINAC2018-WE1A03

[12] C. Gulliford *et al.*, "Demonstration of cathode emittance dominated high bunch charge beams in a DC gun-based photoinjector", *Appl. Phys. Lett.*, vol. 106, p. 094101, 2015. doi:10.1063/1.4913678

[13] F. Zhou, "Review of CW Guns for XFEL", in *Proc. FLS'18*, Shanghai, China, Mar. 2018. http://jacow.org/fls2018/talks/thp1wd01_talk.pdf

[14] F. Sannibale *et al.*, "Advanced photoinjector experiment photogun commissioning results", *Phys. Rev. ST Accel. Beams*, vol. 15, p. 103501, 2012. doi:10.1103/PhysRevSTAB.15.103501

[15] D. Filippetto *et al.*, "Cesium telluride cathodes for the next generation of high-average current high-brightness photoinjectors", *Appl. Phys. Lett.*, vol. 107, p. 042104, 2015. doi:10.1063/1.4927700

[16] F. Sannibale *et al.*, "High-brightness beam tests of the very high frequency gun at the Advanced Photo-injector EXperiment test facility at the Lawrence Berkeley National Laboratory", *Review of Scientific Instruments*, vol. 90, p. 033304, 2019. doi:10.1063/1.5088521

[17] D. Li *et al.*, "Recent Progress on the Design of Normal Conducting APEX-II VHF CW Electron Gun", in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 1891–1894. doi:10.18429/JACoW-IPAC2019-TUPRB097

[18] D. Li, personal communication

[19] C. E. Mitchell *et al.*, "RF Injector Beam Dynamics Optimization and Injected Beam Energy Constraints for LCLS-II", in *Proc. IPAC'16*, Busan, Korea, May 2016, pp. 1699–1702. doi:10.18429/JACoW-IPAC2016-TUPOR019

[20] F. Zhou *et al.*, "First Commissioning of LCLS-II CW Injector Source", in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 2171–2173. doi:10.18429/JACoW-IPAC2019-TUPTS106

[21] D. Wang and Q. Gu, personal communication

[22] J. Sekutowicz *et al.*, "Proposed continuous wave energy recovery operation of an x-ray free electron laser", *Phys. Rev. ST Accel. Beams*, vol. 8, pp. 010701, 2005. doi:10.1103/PhysRevSTAB.8.010701

[23] J. K. Sekutowicz *et al.*, "Feasibility of CW and LP Operation of the XFEL Linac", in *Proc. FEL'13*, New York, NY, USA, Aug. 2013, paper TUOCNO04, pp. 189–192.

[24] R. Brinkmann, E. Schneidmiller, J. K. Sekutowicz, and M. V. Yurkov, "Prospects for CW Operation of the European XFEL in Hard X-ray Regime", in *Proc. FEL'14*, Basel, Switzerland, Aug. 2014, paper MOP067, pp. 210–214.

[25] D. Kostin and J. Sekutowicz, "Progress towards ContinuousWave Operation of the SRF Linac at DESY", in *Proc. SPIE*, vol. 11054, pp. 1105406, 2018. doi:10.1117/12.2524952

[26] E. Vogel *et al.*, "SRF Gun Development at DESY", in *Proc. LINAC'18*, Beijing, China, Sep. 2018, pp. 105–108. doi:10.18429/JACoW-LINAC2018-MOPO037

[27] S. Shu, Y. Chen, S. Lal, H. J. Qian, H. Shaker, and F. Stephan, "First Design Studies of a NC CW RF Gun for European XFEL", in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 1698–1701. doi:10.18429/JACoW-IPAC2019-TUPRB010

[28] S. Lal *et al.*, "RF Design Studies of a 1.3 GHz Normal Conducting CW Buncher for European X-FEL", in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 3109–3111. doi:10.18429/JACoW-IPAC2019-WEPTS012

[29] F. Gabriel *et al.*, "The Rossendorf radiation source ELBE and its FEL projects", *Nucl. Instrum. Methods Phys. Res., Sect. B*, vols. 161-163, pp. 1143-1147, 2000. doi:10.1016/S0168-583X(99)00909-X

[30] P. Michel *et al.*, "First Lasing at the ELBE mid-IR FEL", in *Proc. FEL'04*, Trieste, Italy, Aug.-Sep. 2004, paper MOAIS04, pp. 8–13.

[31] A. Arnold *et al.*, "Development of a superconducting radio frequency photoelectron injector", *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 577, pp. 440–454, 2007. doi:10.1016/j.nima.2007.04.171

[32] R. Xiang *et al.*, "Runing Status of SRF Gun II at the ELBE Radiation Center", in *Proc. LINAC'18*, Beijing, China, Sep. 2018, pp. 952–954. doi:10.18429/JACoW-LINAC2018-THPO125

[33] J. Teichert *et al.*, "Experiences with the SRF Gun II for User Operation at the ELBE Radiation Source", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 4145–4147. doi:10.18429/JACoW-IPAC2018-THPMF040

[34] J. Knobloch *et al.*, "BERLinPro - A Compact Demonstrator ERL for High Current and Low Emittance Beams", in *Proc. LINAC'10*, Tsukuba, Japan, Sep. 2010, paper TUP007, pp. 407–409.

[35] B. Kuske *et al.*, "Conceptual Design Report BERLinPro", HZB, 2012. https://www.helmholtz-berlin.de/media/media/grossgeraete/beschleunigerphysik/berlinpro_MAB/BPro_in_detail/Publications/bERLinPro_CDR.pdf

[36] T. Kamps *et al.*, "Status and perspectives of superconducting radio-frequency gun development for BERLinPro", *J. Phys.: Conf. Ser.*, vol. 298, p. 012009, 2011. doi:10.1088/1742-6596/298/1/012009

ISBN: 978-3-95450-210-3 doi:10.18429/JACoW-FEL2019-WEA01

[37] A. Burrill *et al.*, "First Horizontal Test Results of the HZB SRF Photoinjector for BERLinPro", in *Proc. IPAC'15*, Richmond, VA, USA, May 2015, pp. 2768–2770. doi:10.18429/JACoW-IPAC2015-WEPMA011

[38] A. Neumann *et al.*, "The BERLinPro SRF Photoinjector System - From First RF Commissioning to First Beam", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 1660–1663. doi:10.18429/JACoW-IPAC2018-TUPML053

[39] T. Kamps, personal communication

[40] R. Hajima *et al.*, "Design Study of the Compact ERL", KEK Report 2007-7/JAEA-Research 2008-032, 2008.

[41] N. Nakamura *et al.*, "Present Status of the Compact ERL at KEK", in *Proc. IPAC'14*, Dresden, Germany, Jun. 2014, pp. 353–355. doi:10.18429/JACoW-IPAC2014-MOPRO110

[42] T. Konomi *et al.*, "Development of High Intensity, High Brightness, CW SRF Gun with Bi-Alkali Photocathode", in *Proc. SRF'19*, Dresden, Germany, Jun.-Jul. 2019, pp. 1219–1222. doi:10.18429/JACoW-SRF2019-FRCAB4

[43] T. Konomi *et al.*, "Development of SRF Gun Applying New Cathode Idea Using a Transparent Superconducting Layer", in *Proc. ERL'17*, Geneva, Switzerland, Jun. 2017, pp. 1–3. doi:10.18429/JACoW-ERL2017-MOIACC002

[44] J. Hao *et al.*, "Recent Progresses on DC-SC Photoinjector at Peking University", in *Proc. SRF'05*, Ithaca, NY, USA, Jul. 2005, paper THP24, pp. 515–517.

[45] G. Zhao *et al.*, "Tunable High-power Terahertz Free-Electron Laser Amplifier", in *Proc. FEL'15*, Daejeon, Korea, Aug. 2015, pp. 305–307. doi:10.18429/JACoW-FEL2015-TUB05

[46] Y. Q. Liu *et al.*, "Engineering Design of Low-Emittance DC-SRF Photocathode Injector", presented at the FEL'19, Hamburg, Germany, Aug. 2019, paper WEP056, this conference.

[47] S. Zhao *et al.*, "Performance Optimization of Low-Emittance DC-SRF Injector Using Cs2Te Photocathode", presented at the 39th Int. Free Electron Laser Conf. (FEL'19), Hamburg, Germany, Aug. 2019, paper WEP057, this conference.

[48] I. Ben-Zvi *et al.*, "Electron Cooling for RHIC", in *Proc. PAC'01*, Chicago, IL, USA, Jun. 2001, paper MOPA011, pp. 48–50.

[49] V. Litvinenko, "Coherent Electron Cooling", in *Proc. PAC'09*, Vancouver, Canada, May 2009, paper FR1GRI01, pp. 4236–4240.

[50] I. Pinayev *et al.*, "Performance of CeC PoP Accelerator", in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 559–561. doi:10.18429/JACoW-IPAC2019-MOPMP050

[51] S. A. Belomestnykh *et al.*, "Commissioning of the 112 MHz SRF Gun", in *Proc. SRF'15*, Whistler, Canada, Sep. 2015, pp. 1240–1242. doi:10.18429/JACoW-SRF2015-THPB058

[52] K. Jacobs *et al.*, "The Wisconsin Free Electron Laser Initiative", in *Proc. PAC'09*, Vancouver, Canada, May 2009, paper MO4PBC04, pp. 109–111.

[53] R. Legg *et al.*, "Wisconsin SRF Gun Development", in *Proc. ERL'09*, Ithaca, NY, USA, Jun. 2009, paper WG118, pp. 45–49.

[54] J. Bisognano *et al.*, "Wisconsin SRF Electron Gun Commissioning", in *Proc. NAPAC'13*, Pasadena, CA, USA, Sep.-Oct. 2013, paper TUPMA19, pp. 622–624.

[55] SLAC Produces First Electron Beam with Superconducting Electron Gun, https://www6.slac.stanford.edu/news/2018-04-09-slac-produces-first-electron-beam-superconducting-electron-gun.aspx

[56] Bruce M. Dunham, personal communication

[57] H. J. Qian, M. Krasilnikov, and F. Stephan, "Beam Brightness Improvement by Ellipsoidal Laser Shaping for CW Photoinjectors", in *Proc. FEL'17*, Santa Fe, NM, USA, Aug. 2017, pp. 432–435. doi:10.18429/JACoW-FEL2017-WEP008

[58] F. Sannibale *et al.*, "Status, Plans and Recent Results from the APEX Project at LBNL", in *Proc. FEL'15*, Daejeon, Korea, Aug. 2015, pp. 81–84. doi:10.18429/JACoW-FEL2015-MOP024

[59] ELBE SRF Gun II - New High Gradient SRF Gun, 2009 – Today, https://www.hzdr.de/db/Cms?pNid=604

[60] W. D. Kilpatrick, "Criterion for Vacuum Sparking Designed to Include Both rf and dc", *Rev. Sci. Instrum.*, vol. 28, p. 824, 1957. doi:10.1063/1.1715731