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REVIEW OF EXPERIMENTAL RESULTS ON HIGH-BRIGHTNESS PHOTO-EMISSION ELECTRON SOURCES

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The generation of electron beams with high phase space density is one of the principal challenges for the next generation of ultra-short wavelength light sources and for the foreseen linear colliders projects. In this paper we review some of the recent experimental advances in the field of electron sources based on the photoelectric effect.

1 Introduction

1.1 Overview

In the recent years electron sources based on the photoelectric effect have supported operation of many accelerators ranging from colliders (e.g. SLC) to novel light sources (e.g. at ANL, BNL, DESY, JLAB). This kind of electron sources have been supporting advanced beam physics experiments such as plasma-driven accelerator (e.g. ANL, FNAL) and Thomson scattering (E.G. LLNL).

The photo-emission electron source (see earlier reviews from Sheffield ¹ and O'Shea ²) offers many advantages compared to the other popular technologies (e.g. thermionic emission). Firstly, there is a good handle on the initial conditions of the emitted electron bunch. Such initial conditions (transverse and longitudinal distribution) is controlled via the photocathode drive-laser parameters (pulse length, spot size on the cathode, intensity, etc...) and turn out to be an important feature for minimizing the transverse emittance growth. With the availability of ultra-short pulse lasers, the electron bunch length can be made small compared to the radio-frequency (rf) cavity wavelength thereby removing the need of sub-harmonic bunching schemes as in injectors based on thermionic sources. On the other hand, the charge density that can generally be reached with photocathodes is of the kA.cm^{-2} level, approximately two orders of magnitude above thermionic emitters. Finally the use of a polarized drive-laser enables the production of polarized photo-electrons in virtue of the angular momentum conservation.

Because of the charge density considered, the photo-electrons need to be quickly accelerated in order to significantly decrease the space charge forces within the bunch. Hence the photocathode is located on the back-plate of the half-cell of a radio-frequency cavity (rf-gun) or at an extremity of a high-voltage gap (dc-gun) as schematized in Figure 1.

An electron source is generally integrated within an "injector" consisting of accelerating section(s) and focusing element(s) configured in such a way to take

Facility, Location	Gun Type f (GHz)	# of cell	Mission
IRDemo, JLab ⁶	dc	—	high average power FEL
ATF, BNL ⁷	rf, 2.86	1.6	multi-disciplinary facility
LEUTL, ANL ⁸	rf, 2.86	1.6	UV SASE-FEL
SDL, BNL ⁹	rf, 2.86	1.6	UV SASE-FEL
CTF, CERN ¹⁰	rf, 3.0	1.5	CLIC test facility
AFEL, LANL ¹¹	rf, 1.3	10.5	IR SASE-FEL
AWA, ANL ¹²	rf, 1.3	1.6	wakefield acceleration
GTF, SLAC ¹³	rf, 2.86	1.6	LCLS test injector
TTF-1/2, DESY-HH ¹⁴	rf, 1.3	1.6	TESLA test facility + VUV SASE-FEL
PITZ, DESY-Z ¹⁵	rf, 1.3	1.6	injector test facility
FNPL, FNAL ¹⁶	rf, 1.3	1.6	multi-disciplinary facility
MIT ¹⁷	rf, 17.14	1.5	multi-disciplinary facility
Tokai ¹⁸	rf, 2.86	1.6	multi-disciplinary facility
NEPTUNE, UCLA ¹⁹	rf, 2.86	1.6	multi-disciplinary facility
PEGASSUS, UCLA ²⁰	rf, 2.86	10.5	multi-disciplinary facility
APPLE, BOEING ²¹	rf, 0.433	1.5	high average power FEL
ELSA, CEA ²²	rf, 0.144	1.5	high average power FEL + Thomson X-ray source
DROSSEL, FZR ²³	srf, 1.3	0.5	supercond. gun test facility

Table 1. List of some of the representative accelerator test facilities based on photo-electron sources.

advantage of the emittance compensation mechanism ^{3,4,5}. Some possible configurations are presented in Figure 2. For the rf-gun set-up, the two variants widely used are the so-called integrated and split injectors ²⁴. The former configuration (e.g. AFEL at LANL) uses long multi-cell rf-gun cavity with low peak electric field whereas the latter one (e.g. ATF at BNL) is based on a 1-1/2-cell rf-gun cavity operating with high peak electric field closely followed by a booster linac.

1.2 Important parameters

The figure-of-merit when considering the application of the electron source to drive free-electron lasers (FEL) or in the framework of linear colliders is the phase space density. Given the normalized transverse and longitudinal rms emittances $\tilde{\epsilon}_{x,y}$ and $\tilde{\epsilon}_z$ respectively and the bunch charge Q , we define the brightness as the ratio of the bunch charge to the hyper-volume it occupies in the 6-D phase space:

$$B \doteq m_e c^2 \frac{Q}{\tilde{\epsilon}_z \tilde{\epsilon}_x \tilde{\epsilon}_y}. \quad (1)$$

Figure 1. Schematic rendition of an rf-gun (a) and dc-gun (b) based electron sources.

Figure 2. The various photo-emission source configuration used: rf-gun split (a) and integrated (b) design, and the dc-gun design (c).

Here $m_e c^2$ is the electron rest energy. In Eq. (1) the emittances are defined following:

$$\tilde{\epsilon}_x = \frac{1}{\langle p_z \rangle} \sqrt{\langle (x - \langle x \rangle)^2 \rangle \langle (p_x - \langle p_x \rangle)^2 \rangle - \langle (x - \langle x \rangle)(p_x - \langle p_x \rangle) \rangle^2}, \quad (2)$$

where x and p_x are the position and canonical momentum in the phase space. The same type of definition applies for the y and z emittances. In our definition the longitudinal emittance units are keV-mm. Eq. (1) can also be extended to the multibunch case. In the definition of such multibunch brightness, the charge and emittances are those computed over the considered train of bunch:

$$\mathcal{B}_M \doteq m_e c^2 \frac{Q_M}{\tilde{\epsilon}_{z,M} \tilde{\epsilon}_{x,M} \tilde{\epsilon}_{y,M}} \times \mathcal{D}, \quad (3)$$

where $\mathcal{D}$ is the duty cycle and the subscripts M indicated the quantities are taken over the macrobunch. Sources of degradation of this multibunch brightness essentially come from long range wakefields and rf stability issues.

Though it should be underscored that for some applications, the figure-of-merits such as emittance or brightness need to be considered over longitudinal slices along the bunch. For instance the self-amplified stimulated emission (SASE) FEL properties depend upon beam parameters within slices whose lengths are of the order of the so-called “cooperation length”, that is the slippage length between the radiation field and the electron for one gain length. For an X-ray FEL (1 Angstrom wavelength) these slices are typically $\sim 1 \mu\text{m}$ long.

2 Photocathodes and drive-lasers

Given the quantum efficiency η of the photocathode, the drive-laser energy $\mathcal{E}$ and wavelength λ , the charge Q of the photo-emitted electron bunch is:

$$Q = \eta \times \frac{e\lambda}{hc} \mathcal{E}, \text{ or } Q[\text{nC}] \simeq \eta[\%] \times \frac{\lambda[\text{nm}]}{124} \mathcal{E}[\mu\text{J}]. \quad (4)$$

The latter equation is valid for a single-photon photoemission process. The most commonly used photocathode materials along with a few of their properties are summarized in Table 2.

Metallic photocathodes can be used with ultra-violet light as they are stable and “blind” to photons having lower energies. However, due to metallic reflection and internal absorption, the quantum efficiency of such materials is rather low (typically $\eta \sim 10^{-4}$).

In semiconductors photocathodes, the photons must impart enough energy to the electrons in the valence band to reach the conduction band and have enough energy left to escape the photocathode into the surrounding vacuum. The energy difference between the bottom of the valence band and the vacuum level is called the electron affinity E_a and the total energy required is $E_a + E_g$ where E_g is the energy gap between the top of the valence and the bottom of the conduction bands. Alkali Antimonide and Telluride (which are of the positive electron affinity ($E_a > 0$) type) have been used to produced unpolarized highly charged beams with a duty cycle similar to what is required for the TESLA linear collider.

Negative electron affinity (NEA) photoemitters are p-type semiconductors whose surface is treated to “bend” the band structure. In extreme cases, the vacuum level is lower than the bottom of the conduction band. The principal advantages

Material	typ. Q.E.	λ (nm)	lifetime (days)	vacuum req. (T)	in use at
Cu	2×10^{-4}	260	months	$\sim 10^{-7}$	ATF, SDL, Tokai,
Mg	2×10^{-3}	260	months	$\sim 10^{-7}$	ATF
Alkali Antimonide	5×10^{-2}	532	days	$\sim 10^{-10}$	BOEING
Alkali telluride	1×10^{-2}	260	months	$\sim 10^{-9}$	FNPL, TTF,
NEA GaAs (Cs)	5×10^{-2}	780	days	$\sim 10^{-11}$	IrDemo

Table 2. Commonly used cathode material and some of their typical characteristic.

of NEA photocathode include a longer wavelength operation and a higher quantum efficiency compared to the other photocathode types. An example of a NEA photoemitter is Gallium Arsenide (GaAs). It has been used as a photocathode in dc-guns to produce polarized beams with high duty cycle ²⁵.

Although metallic photocathodes can stand relatively poor vacuum, their quantum efficiency is at the 10^{-4} level. Hence the required laser energy for producing 1 nC of charge is of the order of 5 mJ. Driving a high average current accelerator, e.g. an energy-recovery linac-based light source, would require a ~ 100 W average power drive-laser if a metallic cathode would be used. Developing such a laser presents important technological challenges and instead, the so-called “ignited feedback regenerative amplifier” concept was proposed. In this latter scheme a part of the FEL radiation serves to drive the photocathode once a conventional drive-laser has been used for the start-up ²⁷. This concept was recently demonstrated at the TESLA test facility (TTF) where the light produced by the vacuum ultraviolet (VUV) SASE-FEL (wavelength 108 nm) was reflected on a downstream mirror back to the Cesium Telluride cathode to regenerate electron bunches ²⁸.

The photocathode material along with the laser used to produce the electrons sets the initial “thermal” emittance that is the emittance generated because of the excess in kinetic energy of the photo-emitted electrons. The thermal emittance sets a lower limit on the beam emittance that can ideally be reached once the accelerator setup has been optimized. Given the excess kinetic energy K of the photo-emitted electrons, the thermal emittance $\tilde{\epsilon}_{th}$ scales linearly with the drive-laser transverse spot size r on the cathode as ³⁰:

$$\tilde{\epsilon}_{th} \simeq \frac{r}{2} \sqrt{\frac{2K}{3m_e c^2}}. \quad (5)$$

The latter equation assumes (1) the laser spot to be a uniform distribution and (2) the electrons to be emitted isotropically with the average kinetic energy K . To date, detailed measurements of thermal emittance have been reported for NEA GaAs and Copper cathodes only.

For GaAs cathodes, the transverse emittance measurements were performed at the Illinois/CEBAF polarized DC electron source ³¹. The emittance was measured for different drive-laser wavelengths and spot sizes on the cathode. The deduced

thermal transverse energy at $\lambda = 710$ nm was $K = 37$ meV. Recently, a technique to measure the energy distribution of electrons as a function of the transverse and longitudinal energies has been developed and applied to study the distribution of the photoemitted electron from a cooled ($T = 90$ K) GaAs cathode³². It was shown that the obtained population distribution has a sharp peak for transverse thermal energies of about 5 meV for $\lambda = 800$ nm. The comparison of the two aforementioned measurements supports that NEA photoemitters such as GaAs photoemit electrons that are in thermal equilibrium with the crystal lattice. Therefore by cooling this type of cathode, bunches with reduced transverse emittances may be obtained. However, the response time of such photoemitters is typically > 10 ps²⁹ and prohibits a precise tailoring of the initial time-distribution.

For Copper cathodes, a similar measurement was performed at the Source Development Laboratory (SDL) of BNL³³. The emittance measurement was conducted using an S-band rf-gun. To avoid emittance dilution due to rf effects, the gun field and bunch charge were optimized to insure the emittance to be dominated by its thermal contribution. From this latter measurement, the thermal energy was estimated to be $K = 430$ meV for the wavelength $\lambda = 260$ nm, which is one factor of magnitude above the GaAs measurement at room temperature. In Reference³³, the large value of the measured thermal energy (theory predicts 260 meV) was attributed to the non perfect uniformity of the cathode surface: the roughness of the cathode surface can locally enhance the electric field³⁴ and thus impacts the bunch thermal emittance.

3 DC guns

Only one high-brightness photo-emission dc-gun was operated to drive an FEL, the Ir-Demo, at Jefferson Lab. The nominal dc voltage was 350 keV (corresponding to an electric field of ~ 6 MV/m on the cathode surface) and bunch charges up to 130 pC have been extracted from the GaAs cathode during nominal operation³⁵. The gun was coupled to a so-called quarter CEBAF-cryomodule composed of two CEBAF-type 5-cell accelerating cavities with average accelerating gradient of about 10 MV/m. During the FEL operation³⁶, the electron beam emittance measured at the undulator location (at 45 MeV) was $\sim 8 \pm 1$ mm-mrad for 60 pC. Noteworthy, and this is the reason for this gun design, was the sustained lasing at 1.7 kW average power thanks to a bunch repetition rate of 75 MHz CW. At that time, the maximum gun voltage was limited by breakdown due to field emission. Present progress in treating the electrodes using ion implantation foresees the operation of similar dc guns with electric fields as high as 25 MV/m³⁷. A team at JLab has also developed a laser, suited for GaAs cathodes, capable of operating with repetition frequency as high as 2.5 GHz³⁸ thereby providing the possibility to operate a linac downstream of the dc-gun in CW mode that is with a repetition rate equal to the rf frequency of the accelerator. Such a type of operation with a dc-gun is foreseen in the proposed energy recovering linac light source at Cornell³⁹.

	value	units
bunch charge	0.1	nC
laser pulse length (rms)	1	ps
peak cathode E-field	200	MV/m
beam energy	1.05	MeV
typical set of data:		
bunch charge	0.5	nC
beam energy	1.05	MeV
energy spread (rms)	1.5	%
$\tilde{\epsilon}_{\perp}$ (rms)	1	mm-mrad
bunch length (rms)	1	ps

Table 3. Laser and rf parameters for the MIT rf-gun. A set of achieved beam parameters is also given.

4 Radio-frequency guns

Many groups operate test facilities that incorporate rf-gun photo-electron sources. The frequency of rf-guns presently under operation ranges from $f = 0.144$ to 17 GHz. On the beam dynamics point-of-view if one could scale the rf cavity and photo-cathode drive-laser parameters such that the Vaslov equation is kept frequency-invariant^{40,41}, one would gain in operating at higher frequency since the brightness would scale as $\mathcal{B} \propto f^{-2}$. Indeed letting the Vaslov equation frequency-invariant requires the peak electric field to be scaled linearly with the frequency. In extreme cases this may result in problem such as rf-breakdown and field-induced heating. For instance simply scaling the presently achieved peak electric field (140 MV/m) for an S-band ($f = 2.856$ GHz) gun to an X-band ($f = 17.136$ GHz) would result in the unrealistic peak electric field value of 720 MV/m!

4.1 X-band

The Plasma Science and Fusion Center of MIT has worked toward the development of a high-frequency gun operating at 17.136 GHz. This work was motivated by the aforementioned favorable scaling of brightness with the frequency. The gun is a 1.5 cell accelerating structure and incorporates two side wall couplers (one on each cell). It also includes a solenoid for emittance compensation. The main parameters are gathered in Table 3. A multi-slit mask technique was used to measure the transverse emittance just downstream of the rf-gun. For 50 pC charge, the transverse emittance was estimated to be about 1 mm-mrad. To date the peak electric field achieved on the cathode is 200 MV/m and has been limited by rf-breakdown, resulting in a beam energy of 1 MeV approximately. A new gun (2.4 cell) will soon be built in order to boost the beam energy to 2 MeV. It will then be coupled to a 25 MV 17.136 GHz traveling wave linac.

4.2 S-band

The so-called BNL/SLAC/UCLA/ gun operating at 2.856 GHz is one of the most popular configurations. It is used at BNL (both at ATF and SDL), ANL (LEUTL), UCLA (Neptune), and in several Japanese Laboratories (e.g. at Tokai). Since its first version, the rf-gun has been gradually improved (symmetrization of the cavity, new solenoids, new laser port location,...).

At ATF, the gun has driven many experiments and has been used to demonstrate the saturation of the VISA SASE-FEL experiment. At this facility, the emittance has been measured to be 0.8 mm-mrad for a charge of 0.5 nC. Because of the low emittance and to avoid saturation of the beam viewers a special high-betatron function optics was set up and the emittance was inferred by a fit of the beam envelope observed on four viewers. The emittance has been measured at 70 MeV i.e. after acceleration through a 3 m SLAC-type traveling wave section and the measurement involved the minimization of transverse tails induced by dipole mode wake-fields along with beam-based alignment of the quadrupoles. Another study conducted at this facility aimed to investigate the transverse emittance dependence upon the transverse laser spot uniformity on the copper cathode. The laser uniformity is required to be very homogeneous transversely to insure within the bunch that the radial space charge field is linearly dependent on the radius (and thus does not yield a transverse emittance growth). Using neutral density matrix masks of different transmissions, the uniformity of the laser spot was varied and an increase of the emittance by a factor > 2 was observed as the uniformity was changed from a contrast of 0 (uniform spot) to 50 %⁴².

At the source development laboratory (SDL) of BNL, an extended study on the DUV-FEL injector performance has been conducted. Two of the three accelerating sections that compose the accelerator have been operated at zero-crossing to impart a linear correlation between time and energy. The vertical emittance was then measured downstream of an horizontally bending spectrometer dipole. Therefore observing the vertical beam spot variation versus the strength of an upstream quadrupole for various energy (i.e. time) slice provides the slice emittance⁴⁴. At 10 pC, slice emittances close the thermal emittance were measured (~ 0.7 mm-mrad over 200 fs time slices).

Bunch compression using velocity bunching has also been attempted, and peak currents similar to those obtained by magnetic compression were obtained by running the first accelerating section far off-crest⁴⁵.

At SLAC, the gun test facility (GTF) aims to optimize the LCLS injector and demonstrate the parameters required for the LCLS FEL project. Measurements of transverse and longitudinal emittance for various conditions have been conducted⁴⁶. Noteworthy was the technique used to measure the longitudinal emittance: energy profiles downstream of the booster linac have been taken for various phase settings of the booster and a tomographic reconstruction technique in conjunction with particle tracking was used to infer the longitudinal phase space

	ATF	SDL	GTF	SHI	CLIC	units
bunch charge	1	1	1	1	100	nC
laser pulse length (rms)	3	2	1.3	4	4	ps
peak cathode E-field	120	100	120	100	105	MV/m
beam energy	70	200	30	14	40	MeV
typical set of data:						
bunch charge	0.5	0.2	0.2	1	100	nC
energy	70	70	30	14	40	MeV
energy spread (rms)	0.03(u)	0.05	0.025(u)	0.25	-	%
$\bar{\epsilon}_{\perp}$ (rms)	0.8	1.5	1.5	1.2	100	mm-mrad
bunch length (rms)	3	2	1.8	4	4.3	ps

Table 4. Typical photocathode drive-laser and rf parameters for various S-band guns. A set of achieved beam parameters is also given. All the gun presented in this Table operate at $f=2.856$ GHz apart from the CLIC gun for which $f = 3.0$ GHz. Note: “(u)” in the “energy spread” line indicates the quoted energy spread corresponding to the stochastic energy spread (correlations have been removed).

downstream of the rf-gun. The presently achieved parameters (see Table 4) are close to the required LCLS parameters for the low charge operation scenario.

In Japan, Sumitomo Heavy Industry (SHI) has performed beam measurements using a BNL/SLAC/UCLA type rf-gun coupled to an S-band linac ⁴⁷. Downstream of the linac, at energies of 14 MeV, the transverse emittance dependence on the bunch charge and drive-laser pulse shape and length have been investigated. For a uniform drive-laser time profile, the measured transverse emittance of 1.2 mm-mrad for a charge of $Q = 1$ nC has been reported. The emittance has been measured using the quadrupole scan technique and Gaussian distributions were fitted to the profile in order to extract rms values of the beam size and to infer the transverse emittance.

At CERN, the CLIC linear collider test facility 2 (CTF-2) was constructed at CERN to study the generation of 30 GHz rf (required for the CLIC drive beam). It has been driven by a 3 GHz 1.5 cell rf-gun capable of producing the very high charge (100 nC) required for the drive beam. The electron beam requirements are essentially on the peak current, and up to 2.5 kA peak current were obtained after compression. The main parameters of the rf-gun are gathered in Table 4. The CTF-2 facility has also served as a test stand for life-time and quantum efficiency studies of Alkali photocathodes ⁴⁸.

4.3 L-band

An L-band gun operating at 1.3 GHz has been in use at LANL in the context of the Advanced FEL (AFEL) accelerator. The rf-gun consist of a 10-1/2 cell cavity. This gun alone has driven a far-infrared SASE FEL ⁴⁹. The slice emittance has been measured by performing streak camera measurements performed together with a quadrupole scan ⁵⁰. Thus the analysis of the beam size evolution versus the

quadrupole strength for different time slices allows an indirect measurement of the slice emittance (measured slice emittance at 1 nC is about 1.6 mm-mrad). This rf-gun has demonstrated operation with 400 mA average current per macropulse. The gun design incorporates a Nitrogen vessel to support possible cryogenic operation thereby cutting ohmic losses in half.

The TESLA test facility (TTF) and the Fermilab/Nicadd photoinjector laboratory (FNPL) have both been operated with L-band ($f = 1.3$ GHz) rf-guns of the same design. This 1.6 cell rf-cavity was designed and manufactured at Fermilab⁵¹. The rf-gun was originally designed in the framework of the TESLA linear collider project to produce long macropulse trains and experimentally its operation with rf-macropulses of 800 μ sec length was demonstrated. Typical transverse emittances measured in the 17 MeV section of the TTF injector are about 3.5 mm-mrad for a 1 nC bunch⁵². This rf-gun has driven a vacuum ultraviolet SASE-FEL in the saturation regime⁵³. At FNPL, a series of measurements along with their comparison with numerical simulations have been performed on the gun⁶¹. Recently by immersing the photocathode in a magnetic field and using a linear transformation that decomposed the angular momentum into its transverse momentum components⁶², flat beams (that is beams with $\bar{\epsilon}_y/\bar{\epsilon}_x \ll 1$) were produced⁶³. As far as the TTF facility is concerned, a second generation gun that incorporate a co-axial input coupler is under commissioning at the injector facility of DESY-Zeuthen. The inclusion of a coaxial coupler with a doorknob transition renders the cavity axi-symmetric thereby avoiding the potential transverse emittance degradation due to the time-dependent kick induced by side coupler located at the full-cell as in the present design. This improved rf-gun is foreseen to be incorporated in the TTF-FEL user facility.

At Argonne, the AWA team uses a 1.3 GHz rf-gun to produce very high charge (~ 100 nC) bunches for beam-driven wakefield acceleration. Similarly to the case aforementioned of CTF-2 (previous section), the figure-of-merit for beam driven plasma acceleration is the peak current of the drive-beam rather than transverse emittances.

4.4 VHF and UHF band

In the 90's two low frequency guns have been operated at BOEING and CEA-Bruyère le chatel (France).

At Bruyères-le-châtel, the ELSA facility incorporates a 144 MHz rf-gun followed by a linac section operating at 433 MHz. Because of the long bunch length (and thus very small linear charge-density) the achieved emittance at 1 nC is about 1 mm-mrad⁵⁵. The ELSA accelerator has been operated with a macrobunch of 150 μ sec at a frequency of 10 Hz, each macropulse consists of about 2000 bunches. The facility was designed to drive a high power infrared FEL and is about to be upgraded to an X-ray Thomson source²².

	TTF	FNPL	AWA	AFEL	units
bunch charge	1-8	1-7	100	1-4	nC
laser pulse length (rms)	8	4-10		1.5	ps
peak cathode E-field	40	40	80	20	MV/m
beam energy	20	20		15-20	MeV
typical set of data:					
bunch charge	1	1	-	1	nC
energy	17	18	-	15	MeV
energy spread (rms)	0.03(u)	0.25	-	0.2	%
$\tilde{\epsilon}_{\perp}$ (rms)	3.5	3.5	-	1.6	mm-mrad
bunch length (rms)	8	8	-	3.5	ps

Table 5. Typical photocathode drive-laser and rf parameters for various L-band guns. A set of achieved beam parameters is also given. All the gun presented in this Table operate at $f=1.3$ GHz. Note: “(u)” in the “energy spread” line indicates the quoted energy spread corresponding to the stochastic energy spread (correlations have been removed).

	ELSA	BOEING	units
bunch charge	1-10	1-7	nC
laser pulse length (rms)	26	10	ps
peak cathode E-field	25	25	MV/m
beam energy	19	5	MeV
typical set of data:			
bunch charge	1	3	nC
energy	19	5	MeV
energy spread (rms)	0.1(u)	2	%
$\tilde{\epsilon}_{\perp}$ (rms)	1	5	mm-mrad
bunch length (rms)	25	11	ps

Table 6. Typical photocathode drive-laser and rf parameters for the two low frequency guns (ELSA and BOEING). A set of achieved beam parameters is also given. Note: “(u)” in the “energy spread” line indicates the quoted energy spread corresponding to the stochastic energy spread (correlations have been removed).

At BOEING defense and space center, a high average FEL including an energy recovery scheme was operated in the 90’s. Noteworthy was the ability to produce electron bunches out of a 433 MHz rf-gun with the record duty cycle of 25% resulting in an electron beam average power of 160 kW ⁵⁶.

These two low frequency designs operate with rather low electric peak field on the photocathode, about 25 MV/m, and with long (Gaussian) drive-laser pulse length of about 20 ps rms. Because of the latter fact, the charge density is reduced and so are the space charge forces.

4.5 Superconducting radio-frequency guns

The operation of a photocathode inside a superconducting resonator was proposed in Reference ⁵⁸ and a first test was performed in the early 90's using a 2.8 GHz niobium cavity ⁵⁹. At that time, the cavity peak electric field was only about 1.5 MV/m. Recently, a major breakthrough was achieved by the DROSSEL collaboration: At Forschungszentrum Rossendorf, a superconducting rf-gun ⁵⁷ was operated with a field as high as 15 MV/m. The proof-of-principle cavity consists of an half cell of the TESLA cavity geometry with its large diameter side terminated by a shallow cone (see Fig. 3) that provides some radial focusing to compensate for the absence of a solenoid ^a in the vicinity of the cavity ²³. Since the photocathode cannot be in thermal contact with the cavity, a special rf-filter (so-called "choke filter") was implemented to avoid the rf-power from flowing through the cathode coaxial manipulator system thereby preserving the high quality factor of the cavity. At a later stage, the DROSSEL collaboration envisions to develop a multi-cell cavity superconducting rf-gun to serve as an injector for the ELBE ⁶⁰ FEL.

Figure 3. Picture of the Nb half cell cavity for the proof-of-principle srf-gun of Forschungszentrum Rossendorf (Courtesy of D. Janssen).

5 Conclusion & Outlook

Electron sources based on rf-guns have provided electron beams with the required high phase space density to drive short-wavelength single-pass FELs: recently

^aa magnetic field above the critical field (for Niobium $B_c \simeq 200$ mT) would break the Cooper pairs responsible for the superconductivity.

two of these devices were operated in the saturation regime at ANL (LEUTL) and DESY (TTF). Rf-guns can sustain high peak field but cannot simultaneously provide long rf-macropulses: to date the highest duty cycle rf-gun was operated at BOEING with a peak electric field of only 25 MV/m, an electric field comparable to the foreseen achievable field in dc-guns. The latter type of gun having the advantage to be able to drive accelerators in CW mode as demonstrated in the operation of a kW-level average power FEL at JLab.

As far as the choice of the rf-gun frequency is concerned, Figure 4 compares the brightness of the various sources aforementioned. Given the peak current $\hat{I}$, the brightness defined as:

$$\mathcal{B}_{\perp} = \frac{\hat{I}}{\varepsilon_x \varepsilon_y} \quad (6)$$

has been compared since the longitudinal emittance (especially the uncorrelated energy spread) has not been measured in all the quoted experiments. In this figure there is a weak frequency dependence of the brightness. Though the gun with a significantly higher frequency (MIT gun) does not yet take advantage of the emittance compensation process. In the latter Figure, the brightness dependence on frequency is mainly dominated by the scaling of the peak current versus frequency^b which is in any case increased by compressing the bunch.

The success at FNAL to generate flat beams directly out of the FNPL injector, if included in the design of a future linear collider, would relax the requirements on the electron damping ring. The round-to-flat beam transformation has also found applications in light sources^{64,65}. If one would be able to generate polarized flat beams directly out of an injector, one might be able to remove the need for an electron damping ring. The topic of rf-gun for producing polarized electrons is under investigation^{66,67}, the main challenge being to operate GaAs photocathodes in an rf-gun (or finding another photo-emitter capable of producing polarized electrons). It was suggested that the plane wave transformer rf structure may be a good candidate for such a polarized rf-gun since it has a larger vacuum conductance (compared to standard gun cavities) and thereby offers a higher quality vacuum environment⁶⁸.

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^btypically we have $\hat{I} \propto \omega$ for the presently operated guns.

Figure 4. Comparison of the brightness of various sources quoted in the paper. In this plot the brightness has been computed using Eq.(6).

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