ERL 2009 WG1 SUMMARY PAPER: DRIVE LASERS AND RF GUN OPERATION AND CHALLENGES*

J.W. Lewellen[1], H. Bluem[2], A. Burrill[3], T.L. Grimm[4], T. Kamps[5], R. Legg[6], K. Liu[7], T. Rao[3], J. Smedley[3], J. Teichert[8], S. Zhang[9]

[1] Naval Postgraduate School, Monterey, CA 93943, USA
[2] Advanced Energy Systems, Inc., Princeton, NJ 08824, USA
[3] Brookhaven National Laboratory, Upton, NY 11973, USA
[4] Niowave, Inc., Lansing, MI 48906, USA
[5] Helmholtz-Zentrum Berlin, 14109 Berlin, Germany
[6] University of Wisconsin-Madison, Stoughton, WI 53589, USA
[7] Peking University, Beijing 100871, People's Republic of China
[8] Forschungszentrum Dresden-Rossendorf, 01314 Dresden, Germany
[9] Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA

Abstract

Working Group I of the 2009 Energy Recovery Linac Workshop focused on high-brightness, high-power electron beam sources for energy recovery linacs (ERLs), and relevant technology such as development of drive lasers. The WG1 summary paper was broken into two parts: DC guns and loadlocks; and RF guns and drive lasers. This was done both to retain more manageable paper sizes, and because SRF guns are in an earlier stage of development than DC guns. This paper describes the advances, concepts, and thoughts for the latter topics presented at the workshop.

There are many challenges to the successful operation of SRF guns as high-brightness, high-average-current beam sources. These combine the set of challenges for high-current SRF cavities (fabrication, cleaning and processing, HOM extraction, etc.), with challenges for high-average-current photocathode sources (photocathode fabrication, quantum efficiency and lifetime, drive laser technology, etc.). New challenges also arise from this combination, such as the requirement for having removable cathodes in an SRF cavity. Practical approaches have been, and are currently being, found to address the problems, and the base of knowledge and experience continues to grow.

Alternate ideas are also beginning to make inroads. Hybrid DC-SRF guns, pioneered by Peking University, offer promise for combining the best features of both technologies. Quarter-wave SRF cavities offer compact size for a given frequency, potentially easier fabrication than elliptical cells, and very high transit-time factors for quasi-DC operation. Also, the use of normal-conducting cavities, usually dismissed out of hand due to the required RF power consumption, may become practical with advanced cavity designs.

This paper summarizes the state-of-the-art of drive lasers, cathode development and RF gun-based injectors for ERL beam sources The focus in the field has been on DC and SRF guns to date, but interesting approaches for hybrid DC/SRF guns and normal-conducting RF guns are also presented. The paper concludes with discussions of operational issues and concerns, technical issues related to beam source realization, and future concepts.

SUMMARY ON ERL DRIVE LASERS

S. Zhang and T. Rao

CURRENT STATUS

Significant progress on ERL drive lasers has been seen since ERL07. The status of each drive laser is summarized below based on the reports given by different labs during this workshop (specification details are given in Table 1):

- JLab has replaced its flashlamp-pumped drive laser and commissioned a 25W/532nm diode-pumped MOPA system in 2008. The new drive laser has been driving the JLab ERL FEL with adjustable CW micro-pulse frequency from 75MHz down to below 0.5MHz. The macro-pulse width and frequency are also adjustable up to 1ms/60Hz (limited to 1kHz) for routine machine setup. The system shows better amplitude and temporal stability. Unexpected high degree of phase sensitivity from laser oscillator was observed and still remains a primary concern, although considerable effort has been made to suppress the phase noise. A pulse stacker was also installed to change the laser pulse length and shape [1].
- Daresbury Laboratory's 5W/532nm drive laser was commissioned in 2006 and is running for ERL machine beam operation. The laser system has a 0.2% duty cycle with a fixed 81.25MHz micro-pulse frequency and up to 100us/20Hz macro-pulse structure. An issue of temperature instability has arisen from corrosion inside the cooling circuit. This has caused problems in maintaining the pump diode temperature correctly and stably, resulting in longer pulses and reduced SHG efficiency [2].

Table 1: Summary of Drive Laser Specifications

Lab	JLab	Daresbury	Cornell	BNL
Configuration	MOPA	MOPA	MOPA	MOPA
Gain medium	$Nd:YVO_4$	$Nd:YVO_4$	Yb-fiber	$Nd:YVO_4$
Wavelength(nm)	532 (SHG)	532(SHG)	520(SHG)	532(SHG),355(THG)
Pulse (ps)	20, 50	7, 13, 28	2, 30~40	5~12
Power (W)	25	5	15	10 @ 532, 5 @ 355
Max pulse energy (nJ)	300(75MHz) 2000(2MHz)	60	12	500 (10 MHz)
MicroPulse Freq.(MHz)	Variable SMP[1] ~75CW	81.25CW	1300CW	10MHz CW
MacroPulse (µs) &Freq.	0.2~1000 SS[2]~1kHz	SMP to 100 20Hz	0.1~10 1kHz	SMP~10 SS~100kHz
Pulse contrast	$7x10^4$	$>10^6$ at 532 nm	$\sim 10^6$	$3x10^5$
Amplitude stability (rms)	<1%	~1%	<1%	<1%
Phase stability	0.6ps (rms) (10Hz~40MHz)	<0.65ps (0.1 Hz – 1 MHz)	<1ps	0.5 ps (10 Hz-10 MHz)
Pointing Stability(urad)	20		5 (w. Stabilizer)	2-3
Spatial Shape	Truncated Gaussian	Truncated Gaussian (Gaussian + pinhole)	Top-hat (BS[3])	Planned for: Top-hat (BS)
Temporal shape	S. Gaussian (PS[4])	Quasi-Top-hat (PS)	Quasi-Top-hat (PS)	Planned for: Top-hat (PS)
Potential bunch charge	nC (1% QE)	80 pC (1% QE)	77pC	15 nC (10 %QE)
Achiv. bunch charge(pC)	270 135(routine operation)	~130	10	Pending test
Operation Status	ERL	ERL	Injector	Installed, pending cathode illumination

[1] SMP:single-micro-pulse [2]SS:single-shot [3]BS:beam shaper [4]PS:pulse stacker

- Cornell's drive laser is a 1040nm all-fiber system with 1.3GHz fixed micro-pulse frequency. Temporal shaping by pulse stackers was demonstrated and produced quasi-flat-top electron bunches [3]. A pointing stabilizer was tested and showed improved pointing stability. 15W SHG has been achieved, but attempts to generate higher power were hindered by poor power stability of pump-diodes and fiber holder heating issue. A previously-built 50MHz fiber laser is being resumed for intended emittance measurement [4].
- BNL has received a 5W/355nm/10MHz laser from Lumera as the first step to demonstrate nC charge on future ERL accelerator. The laser installation is underway and the test with cathode is expected in year of 2010. Assuming a 10% QE as demonstrated in the laboratory, this laser with CsK_2Sb cathode can deliver up to 150 mA average current and up to 15 nC/pulse. The pulse selection system allows the selection of arbitrary number of pulses from the pulse train with up to 100kHz repetition rate and CW operation at 10MHz. Flat-top laser distributions have been obtained with a commercial spatial beam shaper and multi-crystal pulse stacker at 532nm on a different laser with similar parameters [5].

DISCUSSION AND PROSPECTS

Laser Power and Pulse Control

With the rapid development of advanced laser technology, the laser power needed for 100s of mA electron beam is not a limiting factor any more. But it still requires significant effort to make any commercial laser a robust ERL drive laser with full control of variable macro/micro pulse structures and high pulse contrast, which are crucial for tuning ERL machines, especially in the 10~100s MHz range. In addition, as showed by JLab's test, proper cooling of GaAs cathodes is necessary in order to alleviate the serious temperature rise induced by laser power deposition into the cathode wafer [1]. This may become less significant with multi-alkali cathodes deposited on metal substrates, especially in an SRF gun environment. Further investigation into the issue is necessary.

Stability

The amplitude stability of all available candidate lasers appears satisfactory. Additional stabilizers may be needed for XFEL machines for less than 10urad pointing stability. A question about the phase stability of the SESAM-mode-locked lasers was raised by JLab, based on their experience. This may need broader observation to compare.

Laser Architecture

The laser architecture is of great importance in case of high power systems (10s~100s of Watts). The MOPA configuration seems to be the preferred choice for such ERL drive lasers which demand both short pulse and high power. The idea of combining fiber lasers as seeds and bulk gain materials as power amplifiers will likely be a feasible approach that takes the advantages of both while avoiding their drawbacks.

Pulse Shape and Duration

Both experiments and simulations have shown that uniform laser distributions in both time and space help to reduce the emittance of electron bunches. Cornell's experiment with pulse stacker shows good agreement between the longitudinal profiles of the laser pulses and electron bunches [3]. Spatial beam shapers are well studied and commercially available, but also very sensitive to laser parameters and alignment. Generation of electron bunches with ellipsoidal distributions via space-charge blowout has been demonstrated at low charge of 15pC [6]. A method to generate ellipsoidal optical pulses was experimentally demonstrated [7], but needs to be tested with a gun and photocathode for verification. Finally, it is worth mentioning that, in addition to the laser pulse shape, the actual pulse duration also plays an important part in the performance of an ERL machine, based on simulation and JLab's experience [1].

PHOTOCATHODES FOR HIGH-CURRENT SRF GUNS

J. Smedley

INTRODUCTION

For ERLs operating up to 1 mA average current, several cathode options are available. As described elsewhere, using metallic superconductors as cathodes is reasonable in this regime [8,9]; lead has been shown to be significantly superior to niobium [10]. Plating the cathode region of the injector back wall with lead has little impact on the operating gradient that can be achieved – peak gradients of 40 MV/m have been demonstrated in cavities with lead cathodes [11,12]. Another potential cathode option for the sub-mA regime is Nb plated with 5nm of CsBr. CsBr has been demonstrated to provide a x50 improvement to copper cathodes [13], and a coating of 5 nm in the cathode region is expected to have minimal impact on the cavity RF performance. Although this cathode has yet to be tested in an injector, preliminary measurements by J. Maldonado achieved a QE of $5x10^{-4}$ at 260 nm. This represents an improvement of x800 compared to the niobium substrate, and a factor of four compared to lead at the same wavelength. On a copper substrate, this cathode has been shown to be resistant to brief air exposure, making it far more rugged than standard semiconductor cathodes.

For operating currents up to 10 mA, Cs_2Te is an attractive option. For operating currents of 100mA and above, three cathode technologies are being investigated in the community: III-V semiconductors with negative electron affinity (principally Cs:GaAs), alkali antimonides and diamond amplified photocathodes. The first two cathodes are "established" technologies both for accelerators [14] and in the broader photocathode community, while the diamond amplifier is an ongoing research project [15,16].

BI-ALKALI EXPERIENCE AT BNL

The alkali antimonides offer high QE at visible wavelengths, with vacuum requirements that are more forgiving than GaAs. In some applications [17], alkali antimonide cathodes are used at atmospheric pressure (of argon and methane)! For the BNL ERL, the primary cathode will be K_2CsSb. This cathode is created by sequential deposition on a warm (150C) substrate. Copper and stainless steel (SS) have been investigated as substrates; SS is clearly superior. Antimony is deposited first, with a typical thickness of 20nm. Potassium is deposited second, with a target thickness twice that used for Sb. Finally cesium is added, while monitoring the QE at 532nm. The cathode is complete when the QE stops rising; at this point Cs deposition is halted and the substrate is cooled to room temperature. Figure 1 shows typical response curves for three cathodes on SS substrates, measured with a lamp source and monochromator. For cathode 3, a lower substrate temperature during deposition was attempted, resulting in a marginal decrease in QE. For cathodes 2&4, the QE was measured with a 532nm CW laser, resulting in close agreement with the lamp values (even with six orders of magnitude more power).

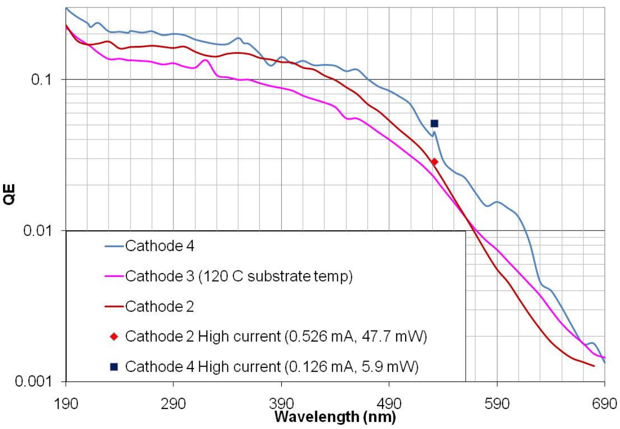

Figure 1: K_2CsSb spectral response.

The dark lifetime of the cathode in the deposition chamber is effectively unlimited – no change in the QE was observed after 40 days of storage at 0.1 nTorr vacuum. The decay of the QE in the deposition chamber was measured (figure 2) under high current density (1.3 mA/mm^2); this is the design average current density for the BNL ERL cathode. To achieve this current density, a CW green laser was focused to an 80 micron FWHM spot on the cathode. In this test, the emitted electrons are dumped into an anode 25 mm from the cathode. This lifetime is therefore a worst case, at least with respect to electron stimulated desorption (ESD). The decay is likely dominated by ESD, as the lifetime depends on the anode bias; no decay was observed for bias voltages under 1keV.

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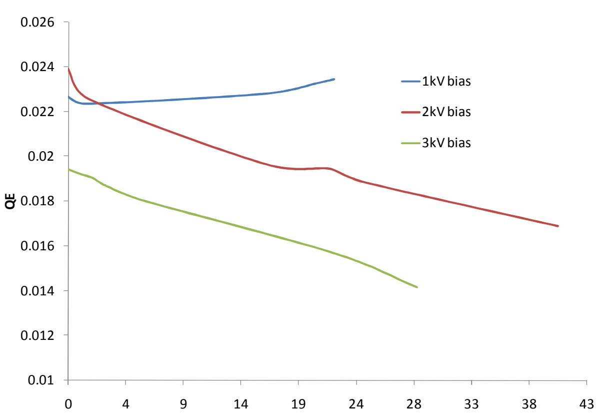

Figure 2: QE decay w/ 1.3 mA/mm^2 current density.

OUTSTANDING ISSUES

Photocathode development for high current injectors is a vibrant area of investigation, and several avenues exist for further work. One test that is sorely lacking is an apples-to-apples comparison of Cs:GaAs and an alkali antimonide (perhaps K_2CsSb) in an injector. Both cathodes have good QE in the green; the vacuum in current DC injectors using GaAs cathodes is easily sufficient for K_2CsSb; thus this seems to be a test that is well within the capabilities of the community.

More generally, continued development of cathode materials is critical as ERLs push to higher average current. Use of the materials analysis tools (UPS/XPS, LEED/XRD, etc.) available at the synchrotrons and nanocenters worldwide will likely produce better (and better understood) cathodes.

SUPERCONDUCTING ELLIPTICAL RF GUNS

A. Burrill and T. Kamps

OVERVIEW

The development of elliptical SRF injectors, pioneered at Wuppertal University in 1991 [18], continues to make strong advances with several interesting projects currently underway. Three laboratories, Brookhaven National Lab (BNL), Forschungszentrum Dresden-Rossendorf (FZD) and Helmhotz Zentrum Berlin (HZB), presented material on elliptical SRF injectors designed for use in ERLs, and each has taken a unique approach to solving the problems associated with providing a small emittance, short electron bunch to the ERL each system is driving. This section will highlight the material presented and try to gauge when each system will see both first beam, and first use in an ERL. This should also serve as a mile-marker for subsequent workshops in order to gauge the advances being realized with this technology.

FZD

The Wuppertal cavity design was subsequently fabricated and tested by D. Janssen et al. in 2000 & 2002 [19,20]. It was a ½ cell 1.3 GHz Tesla style gun with a non-resonant RF choke cavity which served to isolate the normal conducting cathode, both thermally and electrically, from the SRF cavity. This cavity made use of a Cs_2Te photocathode irradiated by a UV laser operating at 263 nm with 5 ps pulses delivered at 26 MHz, and achieved a maximum bunch charge of 20 pC. The system demonstrated stable operation over 7 weeks at 4.2K with a steady Q of 2.5x10^8.

This work led to the design of the current 3 ½ cell SRF injector, shown in Figure 3, designed for use at ELBE (**E**lectron **L**inear accelerator with high **B**rilliance and low **E**mittance) and the focus of the FZD SRF injector work [21]. This gun is a 3½ cell 1.3 GHz Tesla style design utilizing the non-resonant RF choke for cathode insertion. This system has been designed to operate utilizing a Cs_2Te photocathode and is designed for a variety of operating conditions, summarized in Table 2. To date the cavity has produced a 2.1 MeV electron beam with a maximum bunch charge of 200 pC and a transverse normalized emittance of 3 μm at 80 pC. Future plans include connecting the gun to the ELBE accelerator at the end of 2009, as well as the fabrication of 2 new injectors

Table 2: Elliptical cavity gun performance specifications

Facility		**FZD**		**HZB**		**BNL**	
Mode		ELBE	High Charge	HoBiCaT/ Stage 1	B*ERL*inPro/ Stage 2	High Current	High Charge
Electron Energy	MeV	9.5		1.5		2.5	3
RF Frequency	MHz	1300		1300		703	
Design Peak Field	MV/m	50		40		30	35
Achieved Peak Field	MV/m	13.5		45			
Bunch Charge	pC	77	1000	77-1000	77	1400	5000
Repetition rate	MHz	13	0.5	0.03	1300	352	9.38
Laser pulse	ps	4	15	12	15	20	30
Laser wavelength	nm	262		258	355/532	355	
Cathode		Cs_2Te		Pb	CsK_2Sb	CsK_2Sb	
Transverse rms emittance	µm	1	2.5	3	1	2.3	4.8
Average current	mA	1	0.5	$30 \cdot 10^{-3}$	100	500	50
Peak current	A	20	67	6	5	70	166

of similar design that should realize the full 9.5 MeV beam in 2010.

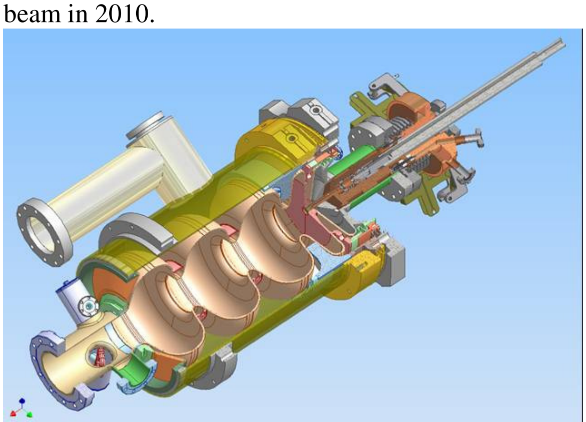

Figure 3. The FZD 3 1/2 cell 1.3 GHz photoinjector.

HZB

The work reported by HZB takes a very different approach to development of an SRF injector suitable for use in an ERL. The approach is staged and the first stage of the development aims at the design of an all SC high brightness gun. This gun, shown in Figure 4, is a 1.3 GHz 1½ cell injector where the back wall of the photoinjector has a small area coated with lead, a superconductor, that is used as the photocathode [9,22]. The goal of this program is to build a robust injector capable of operating at 1 mA average current, 77 pC bunch charge, with a 1 µm emittance. By utilizing the back wall as the photocathode the additional complications associated with introducing a normal conducting photocathode are avoided. This idea grew from the BNL design of a 1.3 GHz ½ cell injector which used the bare Nb surface as the photocathode, however Pb provides ~2 orders of magnitude improvement in quantum efficiency compared to Nb at the same wavelength [10]. To date the gun has been tested at Jefferson Lab in the vertical test area (VTA) and has reached 45 MV/m peak field with a Q of 1.0×10^{10}. Separately the QE of Pb has been measured to be ~0.05% at 258 nm, the desired operating wavelength of the HZB program.

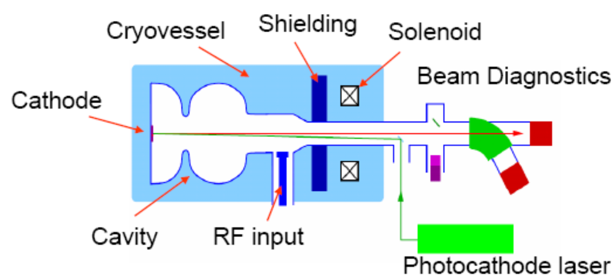

Figure 4. The HZB 1 1/2 cell 1.3 GHz photoinjector layout schematic.

This program is designed as a test-bed for technologies, called B*ERL*inPro [23], for a full scale ERL-based next generation light source. For emittance compensation a superconducting solenoid with NbTi coils will be placed close to the SRF cavity inside the cryovessel. The solenoid field shape and decay are important, especially in the direction of the SRF cavity. Therefore a design with compensation coils or a special flux return yoke is foreseen. The photocathode drive laser is designed to deliver UV laser pulses of a few ps length with 10 µJ energy per pulse, enough to achieve some pC to 1 nC bunch charge for beam dynamics studies in the space-charge dominated regime.

The first milestone of the project, planned for spring 2010, is to perform RF measurements of the interaction between the SRF cavity and solenoid in the HoBiCaT cryovessel. In the next step the drive laser and beam diagnostic devices will be added for first beam operation in autumn 2010.

The testing sequence will then continue with measurement of beam from the injector in the fall of 2010. For the next stage a SC gun cavity with NC cathode insert is foreseen. Then a CsK2Sb cathode is required to reach also high brightness at high average current.

BNL

The BNL SRF injector program began with the aforementioned 1.3 GHz ½ cell injector and has subsequently grown to include the use of a GaAs photocathode in a 1.3 GHz plug gun [24] as well as the design of a novel quarter wavelength choke joint used to isolate the photocathode from the cavity [25]. The main thrust of the BNL ERL injector program is aimed at the testing of a 703 MHz ½ cell injector designed to operate with a CsK_2Sb photocathode illuminated at 355 nm and delivering between 50 and 500 mA average current [26]. The gun, shown in Figure 5, is in the final stages of fabrication and should begin vertical testing in late 2009 with first beam tests in late 2010. The cavity is designed to deliver a 2.5 MeV electron beam to the ERL with 1.4 nC bunches and a normalize emittance of 2.3 µm. The full set of beam parameters are listed in Table 2, and similar to the other two guns discussed includes several different operating regimes in order to fully probe the applicability of this design.

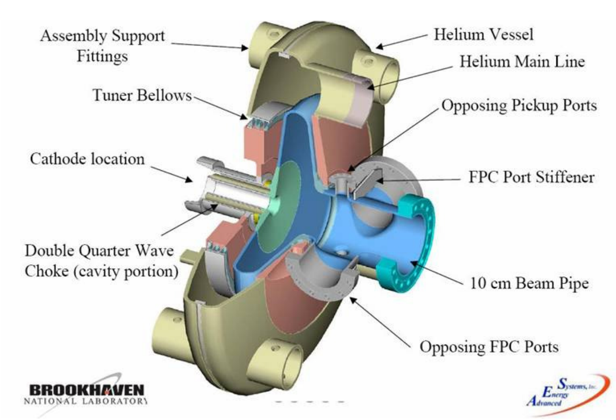

Figure 5. The overview of the BNL 703 MHz SRF injector with the quarter wave choke joint for cathode insertion.

QUARTER WAVE SUPERCONDUCTING RF GUNS

T.L. Grimm

Superconducting RF guns and accelerating cavities for electrons have typically coupled cylindrical waveguide TM010 modes together, while superconducting RF cavities for low energy heavy ions have used coaxial type cavities with TEM modes [27,28]. Recently, coaxial quarter wave cavities have been proposed for electrons due to several potential advantages. The status of quarter wave superconducting RF gun development is reviewed here.

The quarter wave cavity is much more compact than the cylindrical waveguide cavities, thereby allowing operation at much lower frequencies of 100-500 MHz. Figure 6 shows three quarter wave guns under development at Brookhaven National Lab (BNL), University of Wisconsin (UW) and Naval Postgraduate School (NPS) along with their RF frequency and energy gain, respectively. The primary advantages of a quarter wave structure are:

- Cryoplant operation at 4.2-4.5 K
- Small accelerating gap so electric field is effectively DC
- Less RF current on the cathode
- High power, inexpensive CW sources
- Reduced sensitivity to DC magnetic fields
- Improved photocathode lifetime

The compactness of the quarter wave gun reduces the electromagnetic performance compared to traditional cylindrical waveguide cavities at a given frequency, but due to operation at lower frequency the degradation is more than offset. Bulk niobium cavities have demonstrated peak surface fields on the niobium of 100 MV/m and 200 mT at 1.8 K. Typical design levels of half these values are conservatively chosen for a high reliability system at temperatures up to 4.5 K. Therefore, cathode fields around 50 MV/m are possible with extracted electron beam energies of 1 MeV or higher in CW applications. The resulting gap is small compared to an RF period so the fields are effectively electrostatic which improves beam dynamics. Multipacting has been shown to not be a critical issue in these structures as long as good processing procedures and operating vacuum levels are maintained.

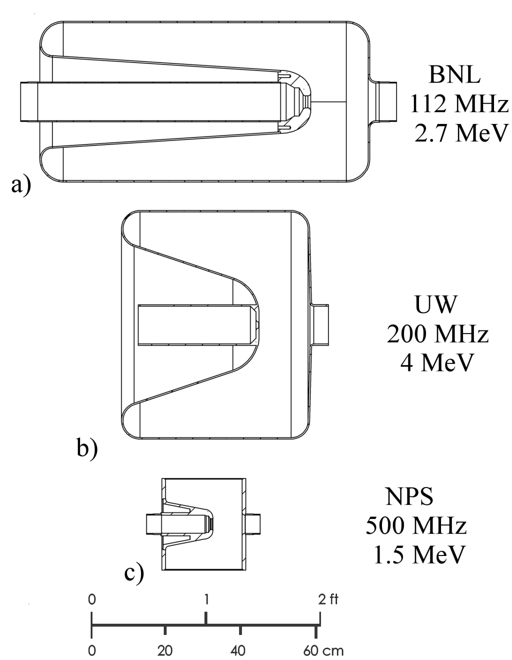

Figure 6. Quarter wave superconducting RF guns under development at: a) BNL, b) UW and c) NPS.

The cathode is usually placed at the end of the inner conductor where the electric fields are largest. Since the amount of charge or current flowing on and off the cathode is reduced, the cathode can be electrically and mechanically isolated. This allows operation of cathodes at cryogenic through room temperature. Figure 7 shows a Superfish simulation of the NPS gun with the cathode slightly recessed to give a Pierce like geometry with electric field focusing at the cathode.

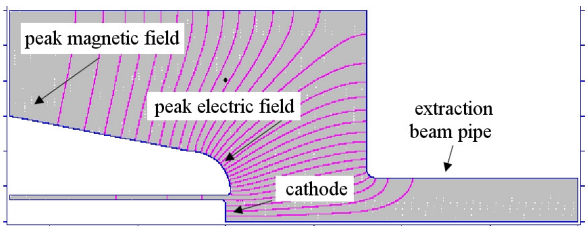

Figure 7. Electric field lines of the 500 MHz NPS quarter wave gun.

Due to cryogenic pumping and cleanroom processing of the cavity, vacuum levels similar to the DC guns are possible. Also, since the electric field in the quarter wave gun is time varying, the cathode damage from ionization along the electron beam trajectory and the subsequent high energy ion back bombardment should be greatly reduced, thereby increasing photocathode lifetime.

A superconducting solenoid can be placed adjacent to the cavity for focusing and emittance compensation. Simulations of all three guns presented here have shown that nC bunches can be generated with the very high brightness necessary for applications such as FELs and high energy electron cooling.

Development of the NPS gun is the most advanced so its design will be presented to show the general characteristics of quarter wave guns. Figure 8 shows the NPS gun cryomodule without the cathode assembly or the axial power coupler.

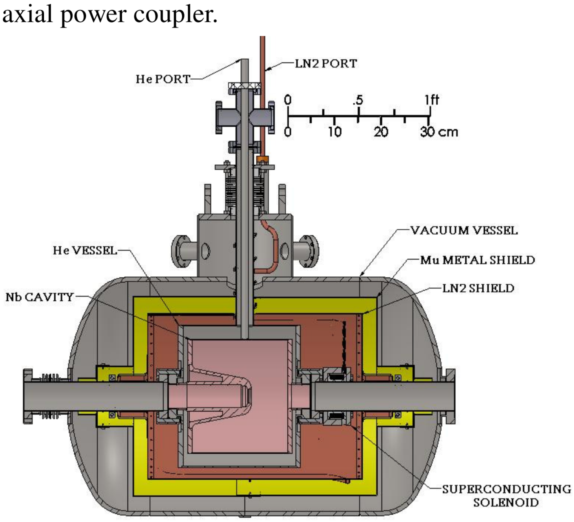

Figure 8. NPS 500 MHz superconducting gun cryomodule

The niobium quarter wave cavity is surrounded by a stainless steel helium vessel to maintain cryogenic temperatures. The niobium-titanium solenoid is on the beamline and has magnetic shielding. The gun cavity and solenoid are surrounded by a liquid nitrogen shield and multi-layer insulation. Finally, a mu-metal shield and low carbon steel vacuum vessel surround the entire system. The insulating vacuum is isolated from the beamline vacuum which is hermetically sealed after processing in the cleanroom.

The cathode assembly and load lock system are attached on the inner conductor side of the quarter wave gun. The power coupler is inserted axially down the extraction beam line to reduce any dipole kicks and to couple strongly to dangerous higher order modes.

Initial demonstration tests and experimental results are anticipated in 2010 for these quarter wave guns. Future developments include coupling the quarter wave cavity to additional cells, high power input couplers with higher order mode extraction, and cathode research with photo, thermionic, field emission and secondary electron emitters. Also the use of multiple modes and frequency operation for focusing and bunch length control can be explored.

HYBRID DC-SRF GUN

K. Liu

The DC-SRF (or SC) photocathode injector developed by Peking University is one of the new candidate low emittance, high brightness electron beam sources. This new design, which integrates a Pierce DC gun and a superconducting cavity, was first proposed by Peking University in 2001 [29]. It has been preliminary demonstrated by the beam experiments with a prototype including a Pierce gun and a 1.5 cell cavity. Energy gain of 1.1MeV was obtained at 4.4 K [30].

To meet the requirement of the ERL-based FEL program at Peking University, an upgraded DC-SRF injector with a 100kV Pierce gun and a 3.5 cell superconducting cavity was designed and manufactured. (Figure 9). The design acceleration gradient, bunch charge, repetition rate and emittance are 13MV/m, 100pC, 26MHz and 1.2 μm respectively [31].

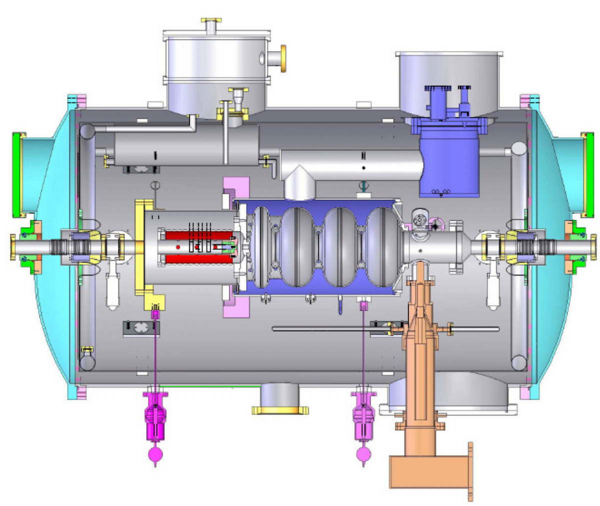

Figure 9. Schematic of 3+1/2 cavity DC-SRF injector

The vertical test of the 3.5 cell cavity, made of large grain niobium, has been carried out at the Jefferson Lab by Dr. Rongli Geng. The initial result was 7MV/m, limited by field emission in the half cell. After heat treatment at 800°C and BCP, the acceleration gradient reached 23.4MV/m and the Q slope is not obvious, as shown in Figure 10. Manufacture of the cryostat, including magnetic shielding of high μ iron, the cavity tuning system, RF power input coupler, liquid helium vessel, liquid nitrogen shielding and supporting components have been finished and the commissioning of the upgraded 3.5 cell DC-SRF photo-injector will be started soon.

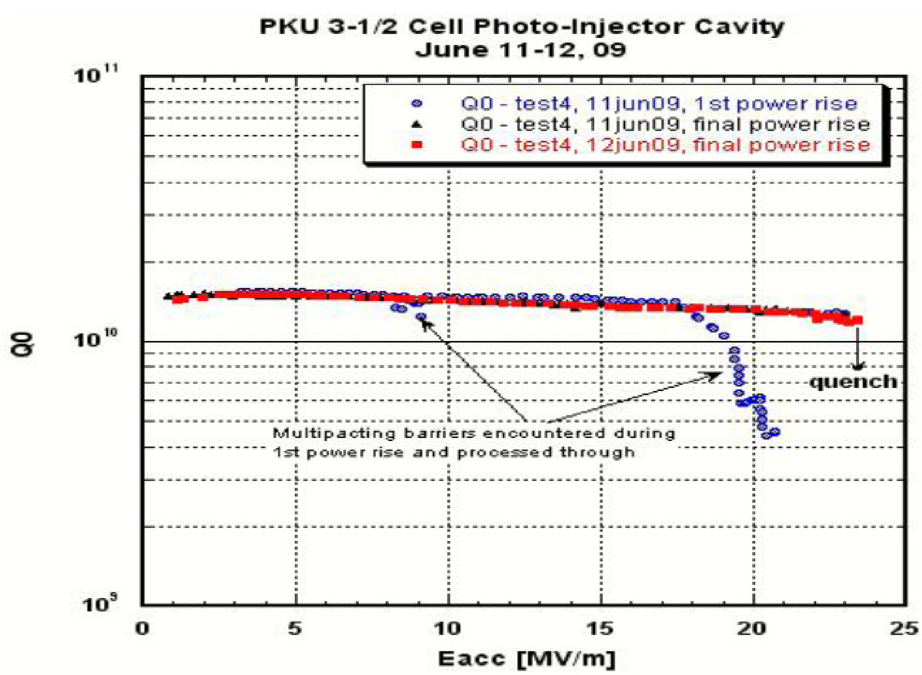

Figure 10. Vertical test result of 3.5 cell large grain Nb cavity

NORMAL-CONDUCTING RF GUN DESIGN ALTERNATIVES

H. Bluem

INTRODUCTION

Normal-conducting Radio Frequency (NCRF) photocathode guns have been very successful in producing low emittance beams in pulsed, high-gradient, low duty-factor operation. For high duty-factor or CW operation, wall losses quickly become the limiting factor, leading to lower accelerating gradients. The problem becomes one of optimizing both the overall losses for a given cathode surface electric field as well as reducing the peak surface losses at local hot-spots. For conventional copper accelerating cavities, the most efficient design is a re-entrant shape which has a high shunt impedance and reasonably evenly distributed wall losses. This shape has tapered nose cones on either side of the interaction gap. The taper is important to spread the wall currents through a larger surface area to improve efficiency and manage the local heat load.

Applying a re-entrant geometry to an NCRF gun can significantly improve the efficiency and allow a higher cathode gradient than would be possible with a pillbox design at the same frequency.

NORMAL CONDUCTING GUNS

The LUX photoinjector [32,33] project sought to develop a multicell photoinjector using a re-entrant design for the cathode cell for a 5% duty factor at 1.3 GHz. However, ERLs require CW electron beams meaning a CW RF gun is required.

To further increase the RF efficiency, one can also reduce the RF frequency. This approach is being considered at BNL [34] as a backup photoinjector to the SRF gun. A mildly re-entrant gun operating at 144 MHz has been designed with a peak cathode field of 8.1 MV/m. Another very low frequency gun design is being pursued at LBNL [35]. This design is strongly re-entrant but only on one side with a very small gap for quasi-DC fields with an operating frequency less than 100 MHz.

One can also achieve the desired results at higher RF frequencies for better compatibility with ERLs [36]. A 1.3 GHz re-entrant gun was designed to serve as a prototype of the concept. Scaling to lower frequency such as 700 MHz should improve the thermal performance. The goal was to limit stress levels to less than 7300 psi in the copper body of the gun. Simulations showed that a cathode field level of 23 MV/m can be supported allowing a transverse emittance less than 1 μm to be achieved. The stress contours at 23 MV/m peak cathode field are shown in Figure 11.

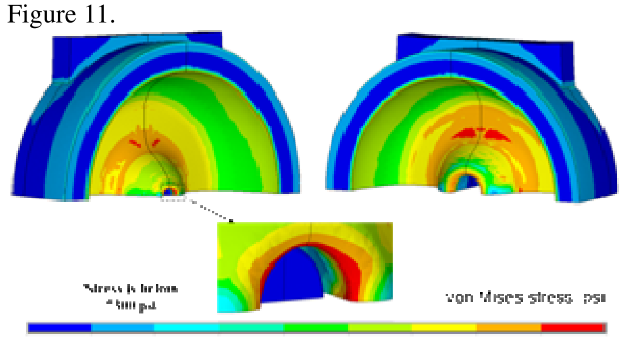

Figure 11: Stress contours on the cavity surface.

Since copper has a non-linear stress-strain curve at low strains, below 0.2%, inelastic analysis was performed to look at more realistic strains and to determine expected frequency shifts of the gun due to operating temperature, coolant pressure and ambient pressure. This analysis shows that the frequency shift at operating temperature is -350 kHz and changes a small amount after each cycle. The results indicate that the frequency shift is an additional -518 Hz after five cycles and -650 Hz after 9 cycles. Looking at the local change in frequency shift, one obtains -50 Hz/cycle at 5 cycles and -20 Hz/cycle at 9 cycles. The change in frequency shift is decreasing with increasing cycles, and it is well within the RF capabilities to track the frequency after each cycle.

Another interesting possibility is to drive the gun through the cathode stalk. The coupling factor can be varied across a very broad range by changing the geometry of the cathode stalk. The target coupling in the subject design is relatively low to accommodate a low average current beam at a 1 MHz bunch repetition rate. Achieving low coupling factors is a challenge in this design, while high coupling factors are easier to achieve. Electrical isolation of the cathode stalk is also possible, allowing a bias voltage to be applied to the stalk to reduce the risk of multipacting.

OPERATIONAL ISSUES – THE FZD EXPERIENCE

J. *Teichert*

PHOTOCATHODES FOR SRF GUNS

For CW operation with medium average currents up to about 10 mA, cesium telluride photo cathodes (PC) seem to be well-suited. This type of semiconductor PC is widely used in normal conducting RF guns [37,38]. Their high photoemission threshold of 3.8 - 4 eV requires UV light, but quantum efficiencies (QEs) up to 20% and operational lifetimes of months have been achieved. The Cs_2Te PCs must be prepared, stored and handled in UHV with a pressure of at most 10^{-9} mbar. For the SRF gun at the FZD, a PC preparation lab was established and systems for the exchange of the PCs have been designed and installed. Figure 12 shows the cathode transfer system attached to the SRF gun.

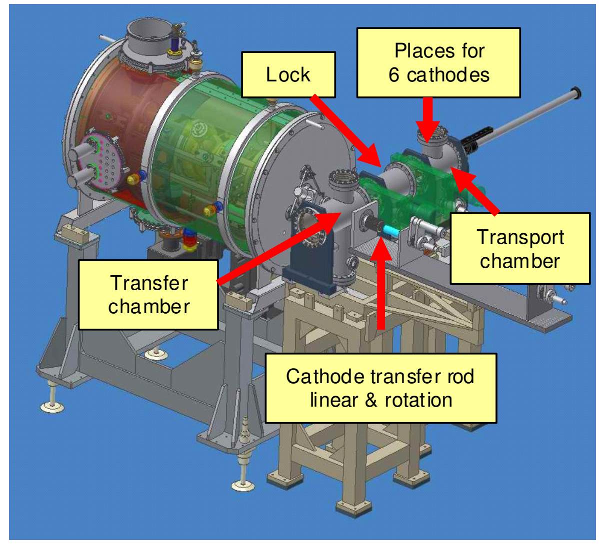

Figure 12. Design of the photo cathode transfer system of the SRF gun at FZD.

A second similar system is connected to the photo cathode preparation equipment. In the transport chamber the PCs are moved and stored before their use in the gun. The design of the cathode plug differs from that in NC guns since the cathode must be separated from the cavity and cooled with liquid nitrogen; further, the prevention of particle production is essential. The FZD design also ensures that the cathodes can be exchanged without warming up the cryomodule.

The evaporation equipment allows the fabrication of Cs_2Te films with the standard technique, where at first a ~10 nm Te layer is deposited following the Cs deposition until the maximum of photo current is reached, as well as the co-evaporation introduced by CERN [39]. The PCs produced with the standard technique in 2008/09 had QEs of 5 – 8% after preparation [40]. Some technical shortcomings caused an increase of vacuum pressure during PC exchange in the transfer system with the result that the PCs had QEs of about 0.1% in the gun [41]. This technical problem was solved. For the first set of Cs_2Te PCs produced in 2009 the long-term behavior is shown in Figure 13. According to the gun specification, 1% QE is sufficient for operation and could be sustained for storage times longer than 60 days. For the cathode transferred into the gun, no QE drop-down was found. This PC was in operation until the end of the run in June without any change in QE. Typical emission currents were between 1 and 20 µA.

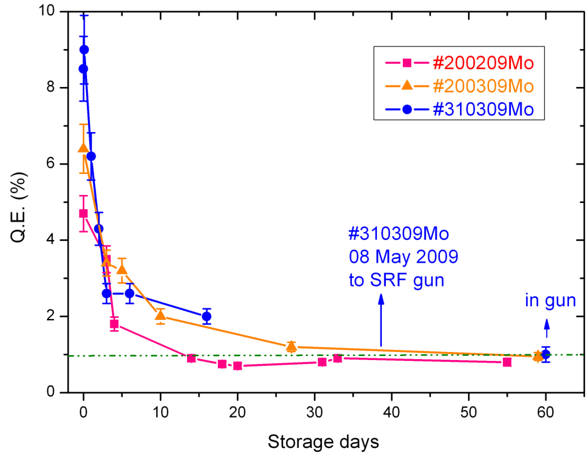

Figure 13. Long-term behavior of Cs_2Te photo cathodes for the SRF gun.

THE ROSSENDORF SRF GUN

The SRF gun for the SC linear accelerator ELBE was developed within a collaboration of the German institutes BESSY/HZB, DESY, MBI and FZD, and was put into operation in 2007. The niobium cavity with 1.3 GHz resonance frequency consists of 3½ cells and an additional choke cell. The full cells have the standard TESLA shape [42] whereas the half-cell has a special design obtained from RF and beam dynamical simulations. In the cavity a normal conducting PC, metallic or semiconducting, can be used. The PC is thermally isolated from the cavity by a vacuum gap, held by a special support system and cooled with liquid nitrogen. The cavity has two tuners (the first for the half-cell and the second for the three TESLA cells together), two HOM couplers, and an ELBE-type input coupler for 10 kW RF power [43]. Details of the SCRF gun design have been published elsewhere [44].

The cavity was fabricated at ACCEL, surface treated (buffered chemical polishing) and cleaned at DESY and ACCEL, and the vertical tests were carried out at DESY. The main problem was the cleaning of the cavity due to the small apertures in the choke and the half-cell and a surface damage produced during treatment [45]. After repeated cleaning and four vertical tests a maximum peak field of 23 MV/m could be achieved, still limited by field emission. After helium tank welding, cryostat assembly and gun commissioning an acceleration gradient of 5.5 MV/m was obtained which corresponds to a peak field of 15 MV/m. The results of the regularly measured cavity performance (unloaded quality factor Q_0 vs. acceleration gradient) are summarized in Figure 14. A high power processing carried out at the end of the run in 2008 improved the gradient to 6.5 MV/m (18 MV/m peak field). The curve obtained in 2009 (11^{th} measurement) verifies the curve from 2007, i.e. any degradation of the cavity performance could not be found after about 500 h beam time with Cs_2Te cathodes in the cavity.

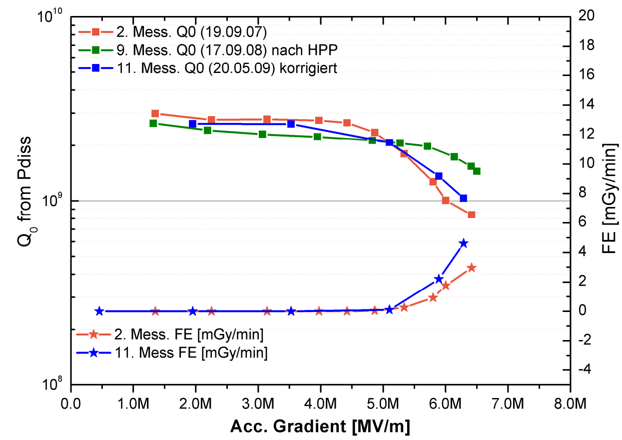

Figure 14. Unloaded quality factor Q_0 vs. acceleration gradient and the corresponding field emission dose (right side). "2.Meas" taken September 2007, "9.Meas" taken after high power RF processing (HPP) of the cavity in September 200; "11.Meas" taken after reinstallation in spring 2009.

Since for the present cavity the designed acceleration gradient could not be achieved and the field at the cathode is rather low, the electron beam dynamics are mainly determined by space charge effects. Thus beam parameter measurements were focused on the question of which bunch charges and emittances could be produced with the given gradient. Figure 15 shows laser phase scan measurements for different laser repetition rates between 2 and 125 kHz at constant laser power of 55 mW. The bunch charge (current) was measured with a Faraday cup about 1 m downstream from the gun. At the optimum laser phase, 300 pC could be produced. The maximum average current achieved up to now was 15 µA at 125 kHz repetition rate and 130 pC.

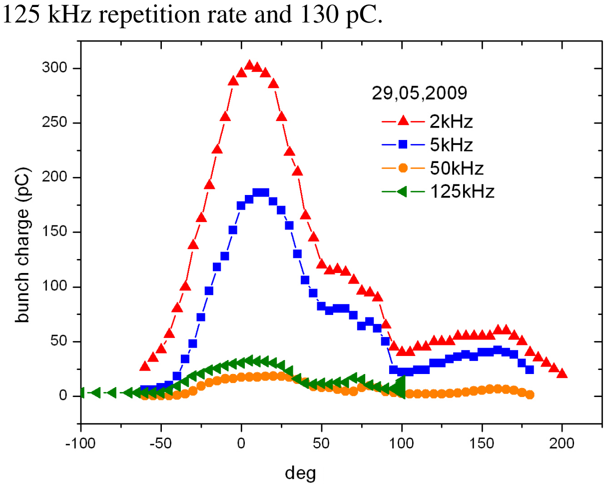

Figure 15. Laser phase scan with 55 mW laser power for different laser pulse repetition rates.

Simulations showed that the coaxial channel between the half-cell back wall and and the cathode stem is the most critical place for multipacting in the cavity. Indeed, multipacting was found at that position during ramping-up the RF. With a DC bias of the cathode up to -7 kV the effect could be eliminated. The strength and duration of this effect were different for different cathodes, which will be studied more systematically. Compared to the quarter wave choke joint of BNL [46] the choke filter design of the FZD cavity does not produce multipacting problems.

The transverse emittance has been measured with the solenoid scan method using the gun solenoid and two following screens, with the results shown in Figure 16.

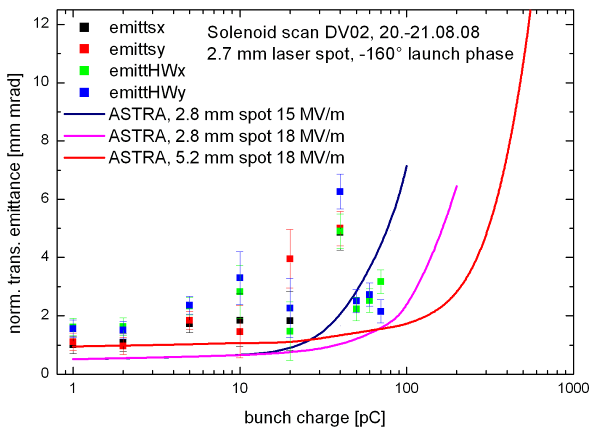

Figure 16. Normalized transverse emittance as a function of bunch charge at optimum laser launch phase measured with the solenoid scan method using beam spot on screen 2. Measurement in horizontal (x) and vertical (y) direction, direct rms beam spot size (emittHM), and Gaussian fit (emitts).

For the measurements, the acceleration gradient was 5 MV/m, the laser spot diameter 2.7 mm. Measurements were carried out up to 70 pC. For higher bunch charges the method could not be applied. The strong space charge effect causes a solenoid current dependence of the beam size which could not be fitted with the theoretical curve. Furthermore the beam shows an increasing halo. The results of the emittance measurements as function of bunch charge are presented in Figure 16.

The measurement agrees sufficiently with the ASTRA simulation performed with similar parameters (2.8 mm Laser spot, 15 MV/m peak field). Further simulations show that an increase of the acceleration gradient to 6.5 MV/m (18 MV/m peak field) and an optimized laser spot of 5.3 mm diameter would allow bunch charges up to 400 pC with transverse emittances ≤ 8 mm mrad, which is acceptable for ELBE.

A summary of the beam parameter measurements carried out in 2008 is given in Table 3. The table also shows the planned parameters for the two operational modes at ELBE with the existing cavity. Two new slightly modified cavities have been designed and are under construction in collaboration with JLab. For these cavities a higher gradient is expected allowing operation with the design parameters given in two last rows of the table. The gun will be operated in two different modes: the FEL mode with 13 MHz and low emittance for the FELs, and the second mode with maximum bunch charge for neutron and positron production.

INSTALLATION AND CONNECTION ISSUES

R. Legg

Several potential problem areas were highlighted during the workshop concerning SRF electron gun installation and interconnection issues. Residual magnetic fields in and around the cryostat must be carefully degaussed or aberrant magnetic fields can be "frozen" into the cavity's structure [47]. The peak field levels only need to be a few gauss to produce an integrated field which distorts the beam. Unfortunately, the field itself may be inside the cryostat making it inaccessible and difficult to do a direct measurement. The resulting beam aberration is difficult to trace since many other magnetic elements may be involved. Careful installation of the cavity is essential to avoid this issue.

The means to put a DC bias of several hundred volts on the cathode to suppress multipactoring in the region between the cavity and the warm cathode after installation

Table 3: Measurement results and design parameters of the Rossendorf SRF gun, showing the results of measurements in 2008, the operational parameters for 2009 with the existing cavity, and the expected parameters for a new cavity with higher gradient.

	present cavity			new "high gradient cavity"		
	measured ´08	FEL mode	high charge mode	FEL mode	high charge mode	
electron energy	2.1 MeV	3 MeV		≤ 9.5 MV/m		
peak field	13.5 MV/m	18 MV/m		50 MV/m		
laser rep. Rate	1-125 MHz	13 MHz	2-250 kHz	13 MHz	≤500 kHz	
laser pulse length (FWHM)	15 ps	4 ps	15 ps	4 ps	15 ps	
laser spot size	2.7 mm	5.2 mm	5.2 mm	2 mm	5 mm	
bunch charge	≤ 200 pC	77 pC	400 pC	77 pC	1 nC	
average current	1 µA	1 mA	100 µA	1 mA	0.5 mA	
peak current	13 A	20 A	26 A	20 A	67 A	
transverse norm. emittance (rms)	3±1 mm mrad @ 80 pC	2 mm mrad	7.5 mm mrad	1 mm mrad	2.5 mm mrad	

was deemed crucial by both the FZD and BNL groups [48,49]. This requires planning for the electrical isolation of the cathode and its support tube and for the connection of the cathode to an external power supply.

Alignment of the cathode with respect to the cavity was also considered key. Initial installation and alignment of the cathode holder requires that the cathode be placed both transversely and longitudinally with respect to cavity very precisely. FZD suggests a precision much better than 0.1 millimeters [50]. The process is further complicated by the differences in shrinkage by the various materials in the cavity and the cathode holder as they are cooled.

Alignment of the solenoid and downstream elements with the cathode spot is important to minimizing emittance growth due to chromatic effects. Cornell [51] uses stages to move their solenoid to the electrical centerline of the beam path from the gun. By adjusting the solenoid position, they minimize the chromatic and steering effects caused by misalignment and they can track the cathode spot as it is moved off-axis to avoid ion back bombardment of the emission site. JLAB [52] sees an increase from 3 to 5 µm caused by the cathode spot being off-axis relative to the solenoid and buncher. The increase does not affect their ability to lase and consequently has not been looked at further.

Solenoids are commonly used for emittance compensation [44,45,46,47]. To move the solenoid closer to the cathode, several groups are using superconducting solenoids (made of Nb, NbTi or high-Tc wires) located within the cryovessel, with cooling typically provided from the helium dewar to the solenoid either with straps or cooling passages. This allowed the solenoid to be placed as close as possible to the cathode for optimal emittance compensation. BNL had further suggested using a bucking coil to cancel the field and allow the solenoid to be placed closer yet to the cathode. At least one design used a niobium shield over the solenoid which excluded field from the cavity in the event of a cavity quench.

Photocathodes are a common element for SRF and DC electron guns. Field emission and / or dark current from photocathodes has been a problem for JLAB [52]; but have not been for Cornell [51] at 250 kV on the photocathode. T. Rao suggested nano-patterning the cathode to limit specular reflection from the cathode which might cause photoemission in the cavity. This would also minimize the effect of reflections in the drive laser transport line causing halo or multiple beams. Certainly care must be taken in selecting the optical elements in the drive laser line to prevent unintended beam effects. This is also a problem as the photon energy of the drive laser is increased for metal cathodes [57] where ordinary optical elements are not transparent, and many materials in the gun cavity may have work functions lower than the photon energy.

RF couplers [58] for the presently planned SRF electron guns are typically coaxial rather than waveguide designs. They have the advantage that they are more compact with a smaller heat leak than the waveguide designs; but the waveguide designs have better power handling capability and are simpler to cool. All current SRF gun designs use coaxial couplers. The consensus at the Workshop for the lack of waveguide-based designs was that compactness and simplicity were the overriding factors in the coupler selection. Another other issue will be vacuum pumping through these couplers as the power requirements go up. With greater power will come increased heat and gas desorption and the need for increased pumping to prevent condensation in the cavity.

JLAB [52] mentioned that they had more problems with their mundane equipment. Conventional facilities for an SRF electron gun and its drive laser include cooling water, liquid N_2, liquid He, AC power, dry N_2 gas, compressed air and an HVAC system of surpassing quality for constant room and water temperatures. There are also associated problems of vibrations, unintended electrical ground paths, stray magnetic fields and instrumentation and control requirements. Finally, or more correctly, firstly, there are the safety and interlock systems [59] to protect the personnel and equipment from injury or damage. All these "low tech" systems must be interfaced to the electron gun and its enclosure and work properly for the gun to start to do its job.

CLOSING THOUGHTS AND COMMENTS

Developments are proceeding apace for both DC and SRF guns. Development of SRF guns has branched into two types, elliptical and quarter-wave cavity geometries, with each having advantages and disadvantages. While there has been more development of the elliptical cavity designs to date, performance data from both designs is expected in the near future.

There are no shortage of problems and concerns for ERL injector development. While some of these, such as cathode selection and conventional facilities, will be common to all ERL beam sources, others are specific to the type of beam source used. Therefore, the increasing number of beam source candidate designs may be seen as a positive development, indicating the great amount of thought and effort being directed to identifying and ameliorating these effects.

ACKNOWLEDGEMENTS

The conveners and participants of Working Group I wish to thank the conference organizers, and our fellows in the community, for a successful and thought-provoking workshop.

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