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High-Average Power Facilities Summary of Working Group 4:

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Abstract. There has been significant progress in the development of high-power facilities in recent years yet major challenges remain. The task of WG4 was to identify which facilities were capable of addressing the outstanding R&D issues presently preventing high-power operation. To this end, information from each of the facilities represented at the workshop was tabulated and the results are presented herein. A brief description of the major challenges is given, but the detailed elaboration can be found in the other three working group summaries.

Keywords: Electron sources, high average power, HVDC gun, SRF gun, NCRF gun, cathodes
PACS:

FACILITY CLASSIFICATION

This paper tabulates the key parameters of the thirteen high-power facilities represented at this workshop [1-13]. The common goal of a high-brightness beam at high-average current and high-energy has driven all facilities represented at this workshop to base their electron sources on photocathodes. The facilities, however, can be divided into three groups based on their method for accelerating the electrons: 6 facilities are based on normal-conducting, radio-frequency (NCRF) guns, 5 facilities are based on superconducting RF (SRF) guns, and 2 facilities are based on high-voltage, direct-current (HVDC) guns. Detailed examination of the relative merits of the various approaches was left to the other working groups as our principle objective is to organize the information into three tables for future reference.

EXPLANATION OF TABLE PARAMETERS

While most of the entries presented in the following tables are self-explanatory, we define a few terms for the sake of clarity. Pulsed machines are defined by micropulse, macropulse, and average characteristics. The characteristics defining the micropulse are charge, Q_{bunch}, bunch fwhm length, t_{bunch} and the micropulse repetition frequency, f_{micro}. The macropulse parameters are the length of the micropulse train, t_{macro}, and the repetition rate of the macropulses, f_{macro}. These quantities then define the peak current ($I_{peak} = Q_{bunch}/t_{bunch}$) and the macropulse current, $I_{macro} = Q_{bunch}f_{micro}$. The average current, I_{ave}, is given as $I_{macro}d.f.$ where the duty factor is $d.f. = f_{macro}t_{macro}$.

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NCRF GUNS

High-power, high-brightness NCRF gun operation is a tradeoff between two competing forces. High peak RF fields are required for high-brightness operation while high-current operation requires low RF fields due to cooling the power dissipated in the walls of the gun. Table 1 lists the six facilities represented at the

TABLE 1. NCRF gun facilities discussed at the workshop.

Facility =>	ANL / AWA J. Power		Boeing D. Dowell	FNAL / A0 Ph. Piot	PITZ F. Stephan		LANL/LEDA D. Nguyen	LBNL VHF gun/J. Qiang	SLAC/LCLS D. Dowell
status	Goal	Demonstrated	Demonstrated / Decommissioned	Demonstrated	Goal	Demonstrated	Under Construction	Under Construction	Demonstrated
avergage current	10 uA	1 uA	32 mA	8 μA	32.5 uA	7 uA		1 mA	0.12 μA
gun/injector	1.3 GHz; 1.5 cell		433 MHz; 1.5 cell	1.3 GHz; 1.6 cell	1.3 GHz; 1.6 cells		700 MHz; 1.5 cells	187 MHz	2.856 GHz; 1.6 cell
energy		7.7 MeV (gun) 15 MeV (NC booster)	1.8 MeV (gun)	4 MeV (gun) 15 MeV (SRF booster)		6.4 MeV (gun)		0.75 MeV (gun)	6 MeV (gun) 135 MeV (booster)
beam power (kW)	0.08	0.008	57.6	0.032	0.208	0.0448		0.75	0.72
peak field		80 MV/m	26 MV/m	35 MV/m		60 MV/m		19.5 MV/m	115 MV/m
RF power (peak/average)		12MW / 0.36kW	0.8MW / 200kW	4MW / 1.6kW		7 MW / 50 kW		0.875MW / 87.5 kW	11.8 MW / 1.7kW
photocathode	Cs2Te	Mg	K2CsSb	Cs2Te		Cs2Te	K2CsSb, FEA	Cs2Te or K2CsSb	Cu
QE/Lifetime		1 e-5/years	2.3 hours	0.5%, for 5 years		~2-3 %; months			0.0038%; ~1 year
macropulse frequency		5 Hz	30 Hz	1 Hz		10 Hz		CW	120 Hz
macropulse duration	50 ns	20 ns	8.3 ms	400 us	650 us	700 us			1.2 us
duty factor		1.00E-07	25%	0.40%	0.65%	0.70%		100%	1.44E-04
macropulse current	38,000 mA	26,000 mA	128 mA	20 mA	0.5 mA	0.1 mA			N/A, single bunch per macropulse
micropulse frequency		1.3 GHz	27 MHz	1 MHz	5 MHz	1 MHz	100 MHz	1 MHz	N/A, single bunch per macropulse
single shot charge		up to 150 nC	1 to 7 nC	up to 20 nC		1 nC		1nC	1 nC
laser pulse length (fwhm)		1 .3 - 20 ps	53 ps	7 ps		20 ps (beer can)		75 ps	6-7 ps
laser radius		1 mm@1 nC; 10mm@100nC	3-5 mm			flat-top (rms) 0.05 --> 0.6 mm			0.6 mm
trans. emittance		5um@1nC; 120um@100nC	5.5 um @ 1 nC	4 um @ 1 nC	0.9 um @ 1 nC	@1nC: 1.26um(100%) ; 0.9 um (90%)		1 um	1.1 um @ 1 nC (95%)
long. emittance		27keV.mm@1nC 330keV.mm@ 100nC	100 keV mm @ 1 nC						~11 keV mm @1 nC
micropulse current (A)		5000	132.0754717	141.8439716		~50 A		13.3	95
5D brightness		0.3	4.4	8.9	61.7	55.6		13.3	74.6
critical tests				diagnostics: bunch compressor; diagnostics: deflecting cavity	*testing min. emittance for high power NCRF gun;			CW NCRF gun test	Produce beam meeting LCLS requirements
high-average power limitations	cannot operate high average power			limited by arcing in the iris	cooling of cavity; RF power from klystron (<130 kW); laser power and repetition rate			88kW power dissipation; RF coupled into gun using loops;	Cooling of small s-band cavities
technical issues & challenges				could be run to 800 useconds; will be replaced with DESY gun	power dissipation; dark current a severe problem; CO2 cleaning greatly reduced the dark current			requires further acceleration and compression	First observation of optical-scale microbunching
R&D opportunities	bunch-to-bunch diagnostic & beam dynamics testing; transverse cavity		None, facility decommissioned	bunch compressor, emittance exchange, diagnostics, transverse cavity	new booster for 20 MeV gain; tomography studies; transverse rf cavity; HE dispersive arm for longitudinal&transverse studies.		cathode testing in NC RF		Limited R&D as gun provides beams for LCLS operations

workshop based on NCRF guns: 3 of which are currently in operation, while 1 has been decommissioned, and 2 are in the planning stages as noted in the table. The highest average beam power NCRF gun to date delivered an average current of 32 mA at a peak 5D brightness of 4.3 A/micron^2 and has been decommissioned. The three NCRF guns that are presently in operation are L-band RF frequency (1.3 GHz) guns and use pulsed RF. The highest average-current for these operating NCRF guns is the PITZ gun which has demonstrated 7 μA and has a goal of 32.5 μA.

Two major challenges for the NCRF source to achieve high-power operation are gun cooling and photocathode survivability. Regarding the former challenge, the PITZ gun operates at an average power of approximately 50 kW and duty factor ~1% to yield a gradient of 60 MV/m. Keeping the average power fixed, scaling the duty factor to 100% implies a reduction in the gradient to 6 MV/m, a gradient nearly sufficient for high-brightness operation. The excellent PITZ result of ~1 micron normalized emittance for 1 nC bunches encourages the community to continue pushing the average power in NCRF guns to 100 kW and higher. Regarding the cathode challenge, many NCRF guns use vacuum robust Cs_2Te photocathodes. These require a high-power UV drive laser, obtained by frequency tripling or quadrupling of the laser IR pulse. This type of laser presents a difficult technical challenge and is not a viable approach for amp-scale operation. For this reason, both past and planned guns use K_2CsSb which has the potential to reach the amp-scale, provided the more stringent vacuum levels can be achieved.

SRF GUNS

High-power, high-brightness SRF guns have great promise and many planned high-current projects are based on their use. Table 2 lists the five facilities represented at the workshop based on SRF guns, of which one is currently in operation, one is under construction, and three are in the planning stages. The promising capabilities of the SRF gun to provide both high average current and high beam brightness has made it the gun of choice for these new facilities.

Major challenges for the SRF gun include: operation of a warm (LN_2 temperature) normal conducting photocathode in an SRF environment, especially at high charge; emittance compensation with a magnetic field from a solenoid; and HOM damping at high current due to the very high Q's of the parasitic modes.

The FZD Rossendorf SRF gun at ELBE has demonstrated an average current of 1 microamp with a goal of 1 milliamp for a CW beam. Similar to the NCRF guns, the photocathode is Cs_2Te. The practical operation of a semi-conductor cathode in a SRF gun is limited by the risk of contamination of the SRF surface turning it into a normal conductor. Therefore an important result of the FZD tests has been the lack of contamination of the SRF surface by the migration of material from the cathode. This group reports no change in the gun's unloaded Q after months of operation.

The AES-BNL SRF gun has been designed to produce an impressive 500 mA and is currently under construction. This gun will be the electron source for an ERL which itself will be an interesting research facility capable of investigating a wide range of topics such as cathode survivability, emittance preservation and beam recirculation dynamics.

TABLE 2. SRF gun facilities represented at the workshop.

Facility =>	FZD/ELBE J. Teichert		AES-BNL I. Ben-Zvi	HZB T. Kamps	NPS J. Lewellen	UW WiFEL B. Legg
status	Goal	Demonstrated	Under Construction	Planned	Planned	Planned
avergage current	1 mA	1 uA	500 mA	100 mA		1 mA
gun/injector	1.3 GHz; 3.5 cells		700 MHz; 0.5 cell	0.6 cell (1.6 cell); choke filter		SRF, QWR, 200 MHz
energy (MeV)	>3 MeV	3 MeV	2-3 MeV(gun); 20 MeV (booster)	1.5 MeV (gun); 6.5 MeV (booster)		5.5 MeV
peak gun field	18 MV/m	13.5 MV/m	15-20 MV/m	10 to 39 MV/m		40 MV/m
photocathode	Cs2Te	Cs2Te	KCsSb; Diamond	CsKSb		CsTe
QE/Lifetime	5% for months	0.1% for months	~2%; (green)	5%; days	TBD	1% or better; months
macropulse frequency	CW	CW	CW	CW		CW
micropulse frequency	100 kHz	100 kHz	9.38 MHz	1.3 GHz		5 MHz
single shot charge	1 nC @ 100kHz	100 pC	5 nC	77 pC		200 pC
laser pulse length	15 ps	15 ps	10 - 40 ps	15-20 ps		30 fs
trans. emittance	2.5 um at 1 nC	3 um for 80 pC	2um @1.4 nC	1 um		<1micron @ 96 MeV
micropulse current (A)	67	6.7	93.3	3.85		50
5D brightness	10.720	1.444	30.5	3.85		50
critical tests	*testing CsTe in SRF gun; Achieved: no change in unloaded Q;		*testing of different cathodes; *testing merger concepts	*variable RF focusing test in SRF gun; SC solenoid in cryovessel	*cathode testing;	ellipsoidal bunch expansion
high-average power limitations	rf couplers: 30kW		klystron power, 1 MW	Power of RF couplers, HOM, emittance by cathode field		current limited by Tesla module RF coupler; 10KW
technical issues & challenges			704MHz SRF; cathode insertion; choke joint;	cathode insert; fundamental power couplers; HOM couplers; Integration of SC/NC solenoid		
R&D opportunities	testing of operating with CsTe cathode, contamination of cavity, lifetime		high power rf couplers; testing of different cathodes in SRF; merger optics; unique location for 500mA expt.	RF focusing by moving cathode back; will have a gun test stand; existing SRF cavity test stand (Hobicat), planned gun test stand	cathode type still to be decided, maybe needle; Cathode testing; new cavity design (for rf guns); new facility for beam physics & technology	ellipsoidal bunch expansion; bunch shaping in blowout mode; warm cathodes in SRF.

HVDC GUNS

The two HVDC guns described at the workshop are based on the Jefferson Lab design and since they inject into SRF linacs they operate continuously. They use Cs:GaAs cathodes which were developed to produce polarized electrons for high-energy and nuclear physics experiments. While these cathodes require exceptional vacuum (10^{-11} torr range), their advantage is having good quantum efficiency at visible wavelengths allowing them to be driven by green (frequency doubled) lasers. The best performance has been achieved by the Jefferson Lab injector which operates at 10 milliamps and is the source for the 10 kW FEL. It is interesting to note that while not represented at this workshop there is considerable work is being done at Cornell University to develop a bright beam HVDC gun [14].

A major technical challenge for the HVDC gun is the need to generate high brightness beam with Q_{bunch} = 1 nC which requires voltages of 500 kV or higher. To date, HV breakdown limits these guns to operate at less than 350 kV.

TABLE 3. HVDC gun facilities represented at the workshop.

Facility =>	Daresbury / ALICE B. Militsyn	JLAB C. Hernandez-Garcia
status	Demonstrated	Demonstrated
avergage current	**6.5 mA**	**10 mA**
energy (MeV)	350 KeV (gun) 8.35 MeV(injector)	350 KV (gun) 9 MeV (injector)
beam power (kW)	54	90
peak field (MV/m)	6	6
photocathode	Cs:GaAs	Ce:GaAs
QE/Lifetime	4%; 102 hours, 1/e	5-7% starting QE; re-cessiate every 2-3 days
macropulse repetition rate	20 Hz	CW
macropulse duration	100 us	CW
duty factor	0.20%	100%
macropulse current	0.0065 A	0.01 A
micropulse repetition rate	81.25 MHz	75 MHz
single shot charge	80 pC	135 pC
laser pulse length	28 ps; green	23 ps (rms)
trans. emittance	1.5-2 um @80 pC	9 um @9MeV
micropulse current	2.86	22.50
5D brightness	0.933	0.278
high-average power limitations	ceramic for HV	*testing ceramic HV operation
technical issues & challenges	ceramic HV problems	ceramic HV problems

COMPARISON OF THE BEAM PROPERTIES

The information in the tables allows a quantitative comparison of the beams at these facilities. Since the applications for these beams require both the high average current and high peak brightness, it's useful to make a scatter plot in the average current vs. peak brightness plane as shown in Figure 1. In order to simplify its interpretation, the peak brightness is defined simply by

$$Peak\ Brightness = \frac{Q_{bunch} / Bunch\ Length(fwhm)}{Normalized\ rms\ emittance^2}.$$

This relation gives brightness values of 100 or less and is expressed solely in terms of the directly measured quantities without additional factors of π or 2 often used to define the brightness. For comparison, the LCLS gun [15] which provides a very bright beam for the 1.5 to 15 angstrom X-ray FEL has a peak brightness of 75 A/micron^2.

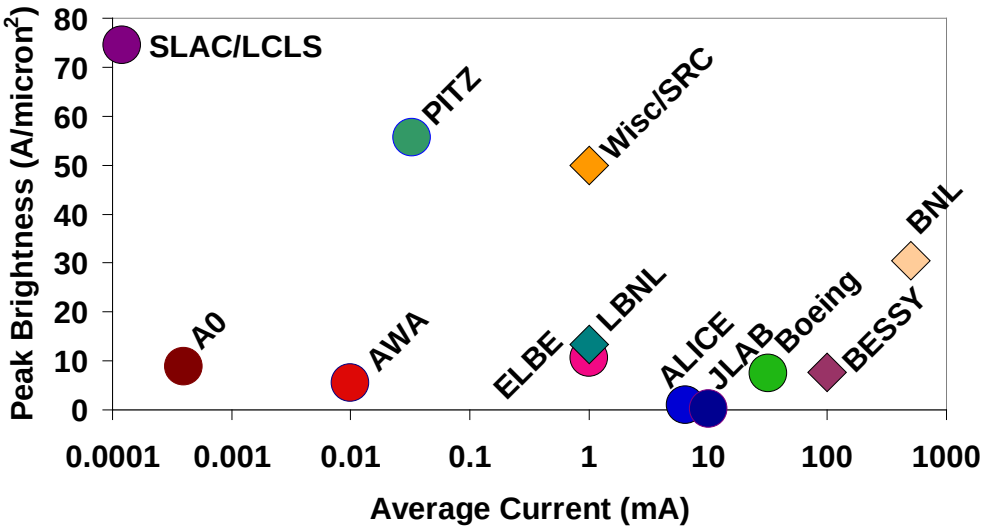

FIGURE 1. A plot comparing the beam characteristics of the various facilities in the plane of peak brightness vs. average current. The operating facilities demonstrated parameters are shown as circles and those under construction or proposed are indicated by diamonds. The method for computing the peak brightness is described in the text.

FACILITIES FOR CATHODE R&D

In addition to the complete accelerator facilities listed above, three groups reported photocathode testing capabilities dedicated to photocathode development and characterization. These facilities have specialized equipment and expertise to fabricate novel photocathodes. The University of Maryland has experimental and theoretical effort dedicated to cathode R&D including the development of dispenser cathodes. They have recently reported depositing Cs on silver, contaminating with CO2, N2O, and O2, and re-depositing Cs to fully rejuvenate the QE to the original 0.15% at 375 nm. [16]. In addition, this group has a strong theoretical research effort [17]. A second group active in cathode R&D is at BNL where they are producing K_2CsSb photocathodes with 3% QE in the green, Cs:GaAs photocathodes for very bright beams from a SRF s-band gun and superconducting lead cathodes[18]. A third group at Vanderbilt University is producing promising theoretical and experimental results for nano-structured field emission cathodes [19].

SUMMARY AND CONCLUSIONS

The increasing number of operating and proposed facilities shows that the field of high-average current, high-brightness electron beam technology is quite active. Whereas a few years ago there were only a couple of facilities dedicated to this research, now there are seven in operation with five being planned or in construction.

There are two basic characteristics of the guns designed for the higher average currents of 100 to 500 milliamps. The first is the RF frequency, except for the HZB (“Helmholtz Zentrum Berlin”) proposal, whether SRF or NCRF, they all operate at

lower RF frequencies of 187 to 700 MHz compared to low duty-factor guns. And second, the preferred cathode material has become K_2CsSb which simplifies the drive laser which allows the use of a green (frequency doubled) drive laser. Thus the consensus is that high average current guns need to be at low RF frequency or DC and use a visible wavelength cathode.

The three fundamental components of the photocathode injector are the gun accelerating structure, the photocathode and the drive laser, and all have seen significant activity since the last workshop. The concurrent investigation of NCRF, SRF and HVDC injectors illustrates the diversity of the field and currently suggests that there is no one path to high-average current. There is also exciting theoretical and experimental cathode research being actively pursued by three groups working on photocathodes and field-emission arrays. And for the drive laser, there has been the naturally occurring advancement in laser technology allowing the drive laser to become a custom acquisition rather than a research project in itself. Therefore these developments and achievements promise a bright future for the high-average current, high-brightness injector and its applications.

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