Overview on superconducting photoinjectors

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The success of most of the proposed energy recovery linac (ERL) based electron accelerator projects for future storage ring replacements (SRR) and high power IR–free-electron lasers (FELs) largely depends on the development of an appropriate source. For example, to meet the FEL specifications [J. W. Lewellen, Proc. SPIE Int. Soc. Opt. Eng. **5534**, 22 (2004)] electron beams with an unprecedented combination of high brightness, low emittance (0.1 μmrad), and high average current (hundreds of mA) are required. An elegant way to create a beam of such quality is to combine the high beam quality of a normal conducting rf photoinjector with the superconducting technology, i.e., to build a superconducting rf photoinjector (SRF gun). SRF gun R&D programs based on different approaches have been launched at a growing number of institutes and companies (AES, Beijing University, BESSY, BNL, DESY, FZD, TJNAF, Niowave, NPS, Wisconsin University). Substantial progress was achieved in recent years and the first long term operation was demonstrated at FZD [R. Xiang *et al.*, in *Proceedings of the 31st International Free Electron Laser Conference (FEL 09), Liverpool, UK* (STFC Daresbury Laboratory, Warrington, 2009), p. 488]. In the near future SRF guns are expected to play an important role for linac-driven FEL facilities. In this paper we will review the concepts, the design parameters, and the status of the major SRF gun projects.

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I. INTRODUCTION

Today there are basically three different types of photoinjectors: the DC photoinjector (DC gun), the normal conducting rf photoinjector (NCRF gun), and the superconducting rf photoinjector (SRF gun).

DC guns easily provide continuous wave (CW) electron beams, but both the low electric field strength at the cathode surface and the short accelerating gap limit the beam quality and the maximum extractable bunch charge [1]. NCRF guns are the most advanced type of electron injectors. They produce high quality beams. However, their low duty cycle can limit the performance when used in superconducting accelerators. Efforts are underway to increase the duty cycle but at the expense of cooling requirements, higher klystron power, and lower power conversion efficiency [2].

SRF guns represent a next step in the development of new photoinjector technologies. By merging the well established NCRF technology and superconductivity, the dissipated rf power is reduced by several orders of magnitude and CW operation for high average currents can be realized. For these guns, however, a cryogenic plant is required with its power consumption outweighing the rf power savings to some extent.

The SRF gun concept was first proposed in 1988 [3]. Four years later, first experiments were done at the University of Wuppertal [4]. In 2002 an important milestone was achieved. For the first time an electron beam was obtained from a SRF gun in the framework of the DROSSEL project at Forschungszentrum Dresden-Rossendorf (FZD) [5]. Inspired by this success several SRF gun R&D projects were launched worldwide.

Different approaches are being applied to overcome the additional difficulties encountered in the SRF gun development as compared to NCRF guns. One of the main problems is that a cathode must be inserted into the superconducting gun cavity. Impurities on the niobium surface generated by the laser irradiation or by ion back bombardment of the cathode may result into a degradation of the cavity performance. This problem, however, is partly mitigated by the high quality cryogenic vacuum in these guns. Because of the low residual gas density, the probability of collisions between electrons and gas molecules is decreased. For this reason fewer ions are available to be accelerated to the cathode and thus the degradation by ion back bombardment is slowed down.

A very important property of the cathode is its laser quantum efficiency (QE) for electron production. The QE determines the maximum extractable bunch charge. Both the amount of impurities produced in the cavity and the quantum efficiency depend on the cathode material (or a respective cathode layer material covering the cathode spot of the niobium cell). There is a trade-off between the two properties of the cathode material, since most potential cathode materials which are well suited as cathodes from the point of view of impurities have low quantum efficiency (e.g. Cu, Nb) and vice versa (e.g. Cs_2Te, GaAs, CsK_2Sb).

For this reason, different SRF gun projects apply different approaches to find an optimum. Taking into account these considerations as well as the fact that cathodes are expected to have a limited lifetime, it is advantageous to

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stick to a technical design of the SRF gun where the cathode can be easily and quickly removed and substituted by a fresh one. To process and reprocess the cathodes, a clean room cathode preparation facility must be provided. In projects with removable cathodes there is a risk for rf power leaking out of the cavity along the cathode channel (i.e., the mechanical gap between the cathode and the gun cell body). For this reason, different kinds of choke filters are used to keep the rf power inside the cavity, whose narrow geometrical openings may hamper the cleaning procedures as compared to the wide iris openings of the TESLA cavities, for example.

Besides the cathodes also the high average beam power up to 1 MW may cause serious problems. The rf main couplers and sources in this class are available today only in the lower UHF band up to 700 MHz. Also the nonresonant higher order mode (HOM) power of some hundreds of watts as well as beam loss on the order of parts per thousand is not negligible any longer.

In contrast to NCRF guns, the emittance compensation by solenoid magnets placed around the cavity is impossible since this would lead to a breakdown of superconductivity. Instead, a solenoid placed at the SRF gun exit, rf focusing at the cathode by its recess and transverse electric mode focusing are proposed to minimize the emittance [6]. Last but not least, problems also arise from the cavity design itself. To realize a high electric field at the cathode surface its phase with respect to the bunch needs to be roughly 90°. For a perfect phase matching of the bunch (starting with zero velocity) especially the first cell has to be much shorter than the usual accelerator cells. Typically, we find half cells or even less and thereby a reduced mechanical stiffness. This requires additional design measures to stabilize the resonance frequency. Among further problems to be solved, we mention good beam matching, avoiding multipacting and special tuner design efforts.

This paper gives an overview on present SRF gun projects around the world. The pros and cons and the present status of the different projects are discussed. Details on available lasers and present cathode development are given elsewhere [7].

II. BASIC TYPES OF SRF GUNS

The different approaches applied by the different SRF gun projects can roughly be divided into four groups (see Fig. 1): (i) normal conducting (NC) cathode + elliptical cavity, (ii) NC cathode + DC gap + elliptical cavity, (iii) NC cathode + quarter wave cavity, and (iv) superconducting (SC) cathode + elliptical cavity.

The basic concepts of these approaches will be described in some detail starting from Sec. III. At the beginning of this section Table I gives a summary of the SRF

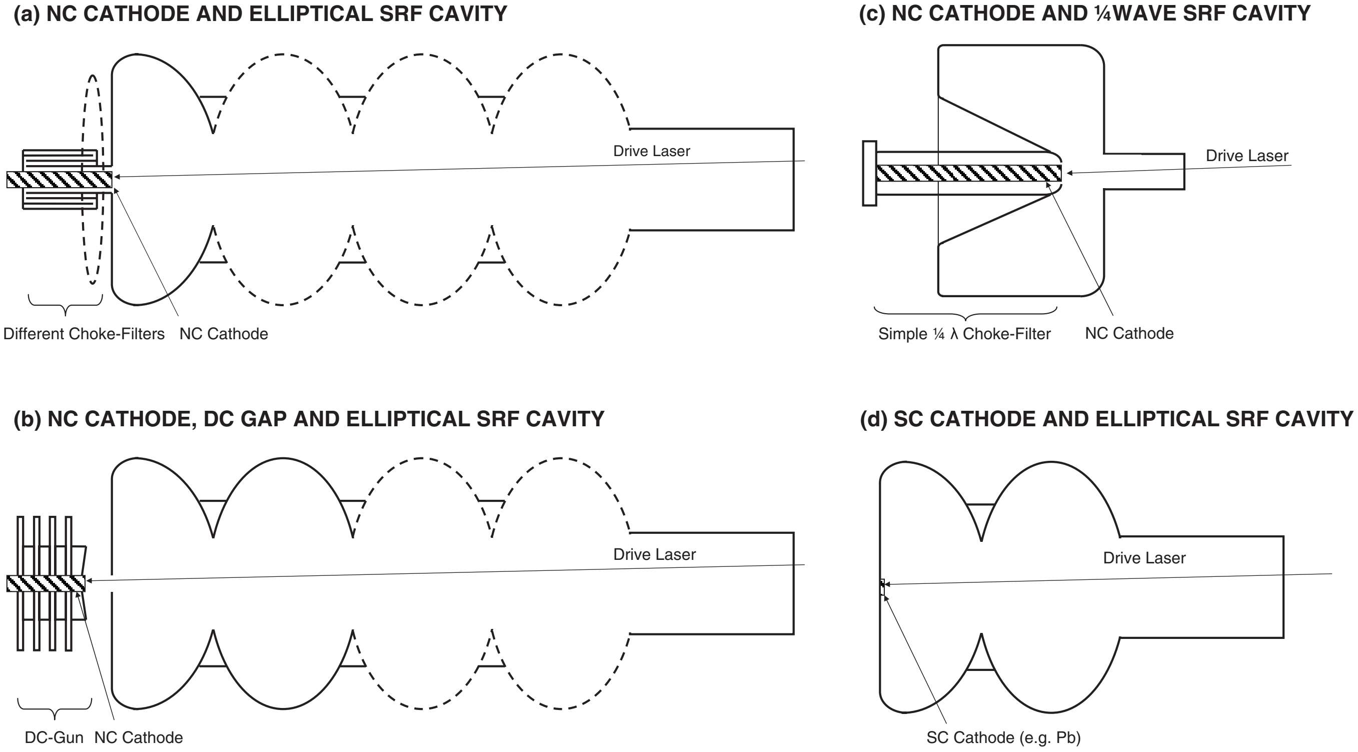

FIG. 1. Generic drawings of the proposed types of SRF guns; (a) NC cathode with either cavity (dotted) or quarter wave (solid) choke filter and 1–4 elliptical cells; (b) NC cathode with DC gap and 2–4 elliptical cells; (c) NC cathode with quarter wave cavity; (d) SC cathode with two elliptical cavity cells.

TABLE I. Comparison of all presently known SRF gun projects and whose expected parameters. Most of the information was provided by the expert named first in the last row. Values taken from other references are additionally marked by an index in the table. Values marked by # are calculated out of V_C and U and those that are marked by * are calculated using P_{diss} and Q_0. Still open parameters are filled in with tbd (to be determined).

		Elliptical cavity + NC cathodes			DC-SC	Quarter wave SRF guns			Elliptical cavity + SC cathodes	
						NPS	WiFEL	BNL		
Parameter	Units	FZD	BNL/AES	HZB BerlinPro	PKU gun	500 MHz	200 MHz	112 MHz	Pb/Nb hybrid gun	HZB HoBiCat
Beam kinetic energy, V_c	MeV	9.4	2	≤ 3.5	5	1.2	4.58	2.7	~ 5	≤ 3.5
Maximum bunch charge, q_{max}	nC	1/0.077	$5/1.4^{(1)}/0.7$	0.077	0.1	1	0.2	5	1	0.015
Normalized transverse emittance, $\varepsilon_{n,t}$	mm mrad	2.5/1	$5/2.3^{(1)}/1.4$	1	1.2	4	0.9	3	1	1
Average beam current, I_b	mA	0.5/1	$50/500^{(1)}/500$	100	1–5	1	1.0	50	<1 rather 0.1	0.0045
Peak current, I_{pk}	A	67/20	$166/70^{(1)}/35$	5	20	50	50	18.5	50	6
Photocathode		Cs_2Te	CsK_2Sb	CsK_2Sb	Cs_2Te	tbd	Cs_2Te	tbd	Pb	Pb
Quantum efficiency, QE	%	1	18	10	1–5	tbd	1	tbd	0.0017	5×10^{-2}
Driving laser wavelength, λ	nm	263	355	527	266	tbd	266	tbd	213	260
Pulse duration (FWHM)	ps	15/4	$30/20^{(1)}/20$	≤ 20	5	10–40	4	270	<20	2 to 3
Bunch repetition rate, f_{rep}	MHz	0.5/13	$10/352^{(1)}/704$	≤ 1300	81.25	10^{-5}–100	5	9.4	<1 rather 0.1	0.030
Gun frequency, f_0	MHz	1300	703.75	1300	1300	500	200	$112^{(1)}$	1300	1300
Operating temperature	K	2	2	2	2	4.2	4.2	$4.2^{(1)}$	2	2
Dissipated power, P_{diss} at the intrinsic Q_0 of	W	26 @ 1×10^{10}	4.2 @ 1×10^{10}	$12.1^{(3)}$ @ 1×10^{10}	$\cdots$	8.6 @ 9.5×10^{8}	42 @ 3.2×10^{9}	$16.6^{(1)}$ @ 3.5×10^{9}	143 @ 5×10^{9}	$12.1^{(3)}$ @ 1×10^{10}
Active cavity length, l_{activ}	cm	50	9.5	17.1	41.7	8	19	20	18.4	17.1
R_{shunt}/Q_0, r	Ω	334	96	$189^{(4)}$, $\beta = 1$	418, $\beta = 1$	185, $\beta = 1$	$155.7^{\#}$	$126.8^{(1)}$	170, $\beta = 1$	189, $\beta = 1$
(R_{shunt} from accelerator definition)			$95.5^{\#}$	$101.4^{\#}$		$176.3^{\#}$		$126.6^{\#}$	$35.2^{\#}$	$101.4^{\#}$
Transit time factor, V_c/V_0	TTF	0.715	$0.888^{(2)}$	$0.54^{(3)}$	$0.74^{(4)}$	0.94	0.87	$0.99^{(1)}$	$\cdots$	$0.54^{(3)}$
Stored energy at E_{pk}, U	J	32.4	$8.4/9.5^{*}$	$14.8^{(3)}$	$\cdots$	2.6	107.2	81.4^{*}	87	$14.8^{(3)}$
Electric cathode field E_{cath}	MV/m	30	20	≥ 10	$\sim 5^{(4)}$	25	45	$19.7^{(1)}$	50–60	≥ 10
Peak electric field, E_{pk}	MV/m	50	35.7	≤ 50	31.8	44	59	51.0	50–60	≤ 50
Peak magnetic flux, B_{pk}	mT	110	74	116	74.5	69.1	90.7	$97.8^{(1)}$	104–125	116
Peak magnetic field, H_{pk}	A/m	87 535	59 000	$\leq 92\,600$	59 285	55 000	72 165	78 000	$(87–99) \times 10^{3}$	$\leq 92\,600$
References:										
Private communication:		A. Arnold	I. Ben-Zvi	T. Kamps (3) A. Arnold	J. Hao (4) F. Wang	J. W. Jewellen T. L. Grimm	B. Legg	I. Ben-Zvi	J. Sekutowicz	T. Kamps (3) A. Arnold
Others:			(1) Ref. [8] (2) Ref. [9]					(1) Ref. [8]		

guns presently under development along with a list of their respective design parameters.

III. NC CATHODE AND ELLIPTICAL CAVITY

Pioneering work in the development of elliptical SRF injectors was mainly promoted by Dr. Dietmar Janssen. Basically, three laboratories picked up this concept: Forschungszentrum Dresden-Rossendorf (FZD), Brookhaven National Laboratory (BNL), and Helmholtz-Zentrum Berlin (HZB), and adapted it to their special beam parameters requirements.

A. FZD 3.5 cell—1.3 GHz SRF gun

The development of the FZD SRF gun started in 1998. In the year 2002 the development turned out to be successful. The first ever electron beam was obtained from a superconducting electron gun [5]. This prototype SRF gun led to the present injector design for the electron linear accelerator with high brilliance and low emittance (ELBE linac). In the framework of collaboration between Deutsche Elektronen-Synchrotron (DESY), FZD, Max-Born-Institut (MBI), and HZB, a 3.5 cell TESLA shaped cavity was built (Fig. 2). It was made from polycrystalline bulk niobium with a residual resistance ratio of 300, which is defined as the ratio of the electrical resistance at room temperature to the electrical resistance at the critical temperature.

The cathode insertion is designed to allow an easy exchange and precise positioning of the Cs_2Te cathodes. Additionally, a resonant superconducting choke filter is needed. It surrounds the cathode and prevents the rf power from leaking out of the cavity. In this manner it works as a bandpass filter. More information can be found in [4,10]. Two TESLA type HOM dampers and one 10 kW CW FZD input coupler are attached to complete the design [11]. The projected cavity parameters are summarized in Table I.

The cavity was fabricated by Research Instruments (RI formerly ACCEL) and processed two times at DESY and at RI, respectively. It turned out that caused by the narrow cathode channel and the presence of the choke filter cell the usual cleaning procedures applied at TESLA cells, i.e., the buffered chemical polishing and the high pressure rinsing are hampered for SRF gun cavities. For this reason, the processing attempts were not as successful as expected. The achieved peak field in the vertical test set at DESY was limited by field emission to $E_{\text{peak}} = 23\ \text{MV/m}$ at $Q_0 = 1 \times 10^{10}$. Details are published in [12,13]. To overcome the cleaning issue, design modifications for the next generation gun cavity are considered [14].

Nevertheless, the commissioning phase of the gun started in September 2007. The Q_0 vs E_{peak} measurement inside the cryomodule revealed an intrinsic quality factor 10 times lower than in former vertical tests. The achievable peak field is again limited by strong field emission and total helium consumption. In the following period, various measurements, done under different conditions, have shown that the performance keeps unchanged independent of whether the cathode is inserted or not. On the other hand, the gradient was improved by applying high power pulsed rf processing in September 2008.

To this day, a stable CW operation up to $E_{\text{peak}} = 18\ \text{MV/m}$ corresponding to $P_{\text{diss}} = 20\ \text{W}$ dissipated helium power is routinely establish (Fig. 3). As far as the cathode is concerned, it was found that after a two year operation of four different Cs_2Te and two metal cathodes (Cu, Mo), respectively, no performance degradation of the cavity was observed.

During commissioning also measurements concerning Lorentz force detuning, microphonics stimulation, helium pressure sensitivity, *in situ* field distribution, and tuner characteristics were done. None of those turned out to be a show stopper. Details can be found elsewhere [15].

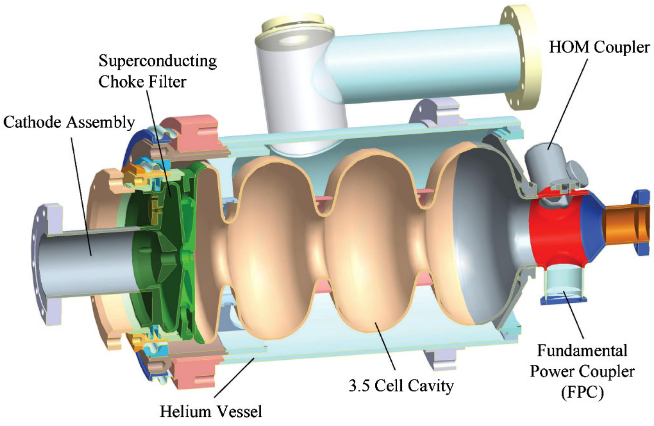

FIG. 2. 1.3 GHz—3.5 cells TESLA shaped FZD SRF gun cavity.

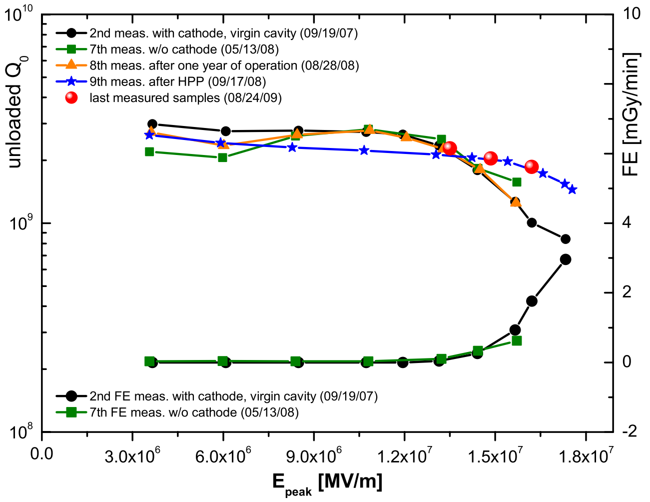

FIG. 3. Intrinsic quality factor Q_0 vs on-axis peak field E_{peak} and the corresponding field emission dose for different measurements.

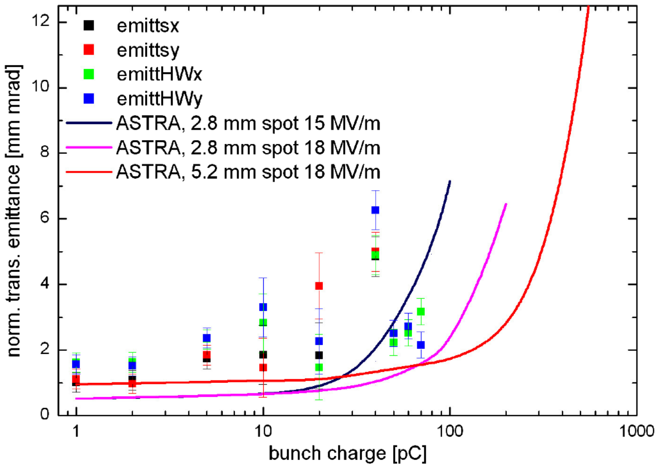

FIG. 4. Normalized transverse emittance versus bunch charge for $E_{\mathrm{peak}} = 15$ MV/m and 2.7 mm laser spot size. The squared dots are measured values (black, red for Gaussian fit; green, blue for FWHM fit) while the continuous curves represent ASTRA simulations.

But as predicted in simulations, multipacting occurs in the gap between cathode stem and cavity. The onset level differs for different cathodes. To take this hurdle a DC bias voltage up to -7 kV and a corrugated cathode surface were applied [16]. More systematic studies are planned.

The preparation of the $\mathrm{Cs_2Te}$ cathodes is done in-house using standard sequential deposition. The quantum efficiency (QE) exceeds 5% during processing but drops to about 1% after transfer into the SRF gun. This value is maintained for at least 60 days at an emission current between 1 to 20 μA (CW). More details are reported in [16].

As a consequence of the limited field gradient, the measured emittance of the present gun is worse than predicted. This is mainly caused by space charge effects and in agreement with simulations. To study this aspect, beam parameter measurements were focused on the achievable transverse emittance in dependence on a given bunch charge. During the first measurements, the gradient and the laser spot size were set to $E_{\mathrm{peak}} = 15$ MV/m (on-axis peak field) and 2.7 mm, respectively. The corresponding kinetic beam energy for an optimized laser phase was found to be 2.2 MeV. The measured transverse emittances for varying bunch charge are shown in Fig. 4 (squared dots).

A maximum energy gain and a bunch charge up to 300 pC were achieved at $E_{\mathrm{peak}} = 18$ MV/m. By increasing the laser spot to 5.3 mm, even 400 pC bunch charge at an emittance of $\varepsilon_{t,n} < 8$ mm mrad is predicted (red curve in Fig. 4). The experimental verification is ongoing. All beam parameters are summarized in Table II and more details are published in [17,18].

A further aspect which is under investigation at the FZD gun is the necessity of HOM couplers. Therefore, a preliminary measurement was done using a 500 nA on-axis beam with a bunch charge of 120 pC. The beam energy again was 2.2 MeV. Figure 5 provides the measured spectra of both HOM couplers as well as the total channel power of the most significant modes. The spectra are dominated by monopole modes. Dipole modes are less excited because the electrons already start at the cavity axis and a radial field in front of the cathode additionally has a focusing effect. To estimate the HOM power for operational parameters (1 mA, 13 MHz), it is assumed that all HOMs are mainly damped by the couplers that are used for the measurement. This is roughly true for all modes up to the beam pipe cutoff frequency (~ 4 GHz). In this case the measured data can be simply extrapolated to higher bunch charges and higher repetition rates. As a result, no dangerous modes are expected and at least for this cavity it can be assumed that no HOM couplers are necessary.

An important milestone was passed in the spring of 2010. The first acceleration of an SRF gun generated electron beam was demonstrated at the FZD. A bunch charge of 120 pC was pushed to 32 MeV using four TESLA cavities of the ELBE accelerator. The next two important steps are the 1 mA high-current operation planned by the fall of 2010 and a cavity upgrade estimated for the beginning of 2011. It should be mentioned that two

TABLE II. Measurement results and designed parameters of the FZD SRF gun.

			Present cavity		New high gradient cavity	
	Units	Measured	FEL	High charge	FEL	High charge
Maximum energy	MeV	3.3	3		9.5	
On-axis peak field	MV/m	18	18		50	
Laser repetition rate	kHz	1–125	13000	2–250	13 000	≤ 500
Laser pulse (FWHM)	ps	15	4	15	4	15
Laser spot size	mm	1–6	5.2	5.2	2	5
Bunch charge	pC	≤ 300	77	400	77	1000
Average current	μA	18	1000	100	1000	500
Peak current	A	20	20	26	20	67
Transverse emittance (rms, n)	mm mrad	3 ± 1 @ 80 pC	2	7.5	1	2.5

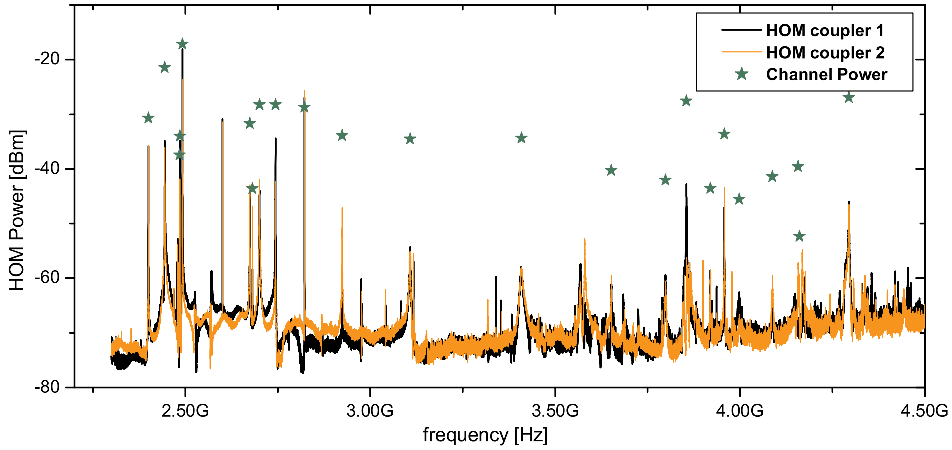

FIG. 5. HOM spectra of both HOM couplers and total channel power of dominant HOM frequencies, measured at a beam current of 500 nA and a bunch charge of 120 pC, respectively.

new improved cavities are currently under fabrication and preparation at Thomas Jefferson National Accelerator Facility (TJNAF).

B. AES/BNL 703.75 MHz—0.5 cell SRF gun

Another very challenging project is running in the framework of collaboration between BNL and Advanced Energy Systems (AES). Since 2004 a superconducting rf gun with several hundreds of milliampere is under development. The gun is planned as an injector for the electron cooler at Relativistic Heavy Ion Collider (RHIC), but it offers also great potential for high-current injectors for linac-driven megawatt-class FELs [8,9,19–21].

The RHIC version (Fig. 6) consists of a half cell superconducting cavity operating at 703.75 MHz, two high power input couplers, a double quarter wave choke filter, and a transfer mechanism for the electrically isolated and LN_2 cooled cathode. The beam pipe diameter is increased to a cutoff frequency above the lowest higher order mode in order to use ferrite HOM dampers. The cavity specifications are summarized in Table I.

The main challenge in this development is the demand on high beam current (500 mA) and a bunch charge up to 5 nC. For this reason, much effort has been put into the cathode R&D to achieve high QE cathodes with long operational lifetime. Promising results are obtained using CsK_2Sb [22]. This alkali antimonide provides a current density of 1.3 mA/mm^2. In addition, a QE of 12% at 532 nm and even 30% at 355 nm are possible using a sequential deposition technique (Fig. 7).

The vacuum required for long time storage of the cathodes has to be in the order of 10^{-10} mbar. Substantial progress has also been reported in the field of diamond amplified cathodes. An emission gain of 40 and a current density of 20 mA/mm^2 were measured [23]. The high-current emission mode, the emission profile, and the electron affinity are the next properties to be investigated.

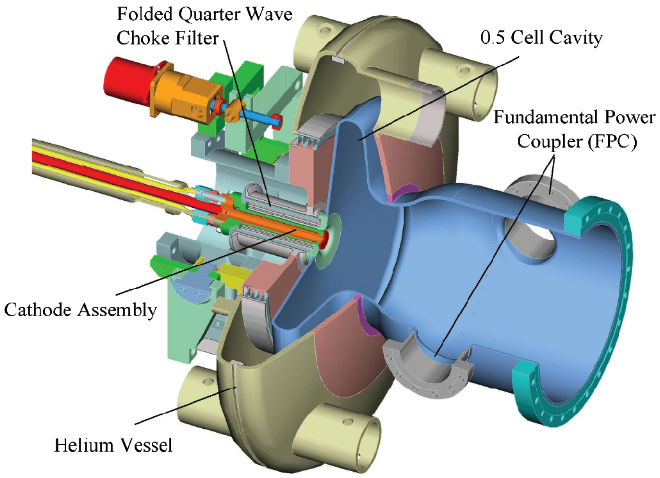

FIG. 6. 703.75 MHz—half cell BNL/AES cavity. Courtesy of Gary McIntyre, BNL.

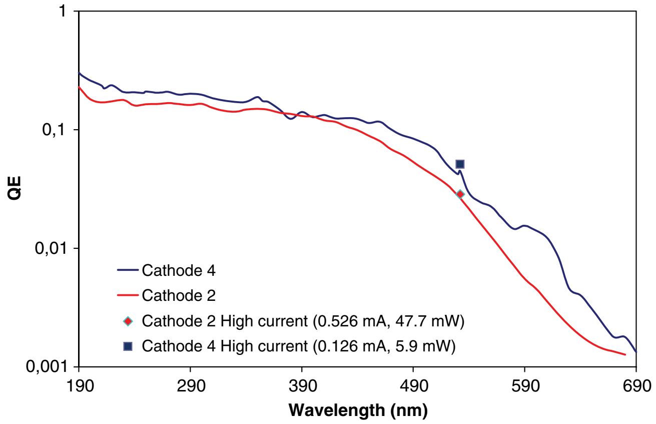

FIG. 7. Spectral response of CsK_2Sb BNL cathodes, measured at room temperature. Courtesy of John Smedley, BNL.

Another bottleneck in the development arises from the very high average power consumption in the order of 1 MW. Couplers capable to transport 2×500 kW power into the cavity are needed. In addition, a low penetration depth of the coupler tip to reduce transverse kicks and strong coupling of $Q_{\mathrm{ext}} \sim 3.7 \times 10^4$ have to be realized at the same time. Moreover, also HOM damping (~ 500 W at 1.4 nC) and beam loss even on the order of parts per thousand are important issues.

In order to find principle design limitations, two 1.3 GHz cavities were built and tested at 2 K. It turned out that strong multipacting (MP) barriers appeared in the folded quarter wave choke filter. For its mitigation, several measures are planned to be taken: anti-multipacting grooves on the choke filter surface, high temperature bake to reduce secondary electron yield, and a biased cathode stalk as applied at the FZD SRF gun [24].

The project is in a very advanced stage [25]. The injector fabrication is underway at AES and the 704 MHz cavity achieved very promising results during the vertical tests, but without the cathode stalk (Fig. 8).

The high temperature SC solenoid is already fabricated and the hermetic string assembly as well as the cryomodule completion are planned by 2010. Furthermore, the cathode transport carts are delivered and the deposition system is tested up to 1.0×10^{-10} Torr. The laser system (5 W, 355 nm, 10 ps, 9.38 MHz), built by Lumera, is under commissioning. The 500 kW CW coaxial couplers are designed and fabricated by Communications & Power Industries. This couplers are provided with "Pringle" shaped tips [26] which were found to be an effective choice for electrical coupling. Their conditioning will be done in-house using a 1 MW klystron. Moreover, also a 1.3 GHz plug gun test system was built to investigate lifetime, QE, and beam properties of GaAs under superconducting conditions.

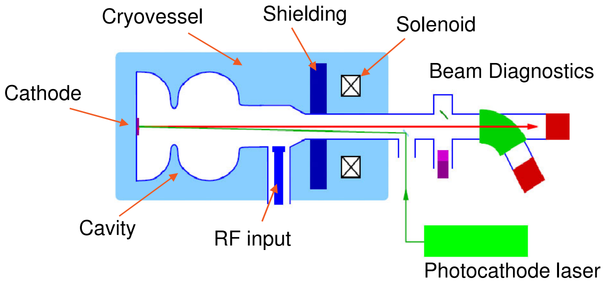

FIG. 9. Generic design of the 1.3 GHz 1.6 cell *BERLinPro* SRF gun. Courtesy of Thorsten Kamps, HZB.

C. HZB 1.3 GHz–1.6 cell SRF gun

In the fall of 2008 the Helmholtz Zentrum Berlin (HZB, former BESSY) made the decision to build *BERLinPro*, an energy recovery linac (ERL) test facility to demonstrate key ERL technologies and to establish ERL know-how at HZB [27]. Based on the experience gained from this facility, a layout of a full-scale ERL-based next generation light source will be prepared.

BERLinPro starts with the development of a 1.3 GHz 1.6 cell SRF photogun using a semiconductor cathode embedded into the cryogenic environment to achieve high average brightness, i.e., low emittance (1 mm mrad) and high average current (100 mA) (see Fig. 9). To promote this ambitious goal, the expertise of the hybrid gun group led by Jacek Sekutowicz and the resources of the HZB (HoBiCaT, beam diagnostics) and the MBI (drive laser) are combined [28,29]. In the first stage a 1.6 cell hybrid gun will be installed inside the HoBiCaT cryovessel. The primary objective of this HoBiCaT gun is beam brightness. The designed target parameter to enter the next level of iteration is 1 mm mrad normalized transverse emittance at 77 pC bunch charge. The first beam operation is expected in the fall of 2010. After successfully passing

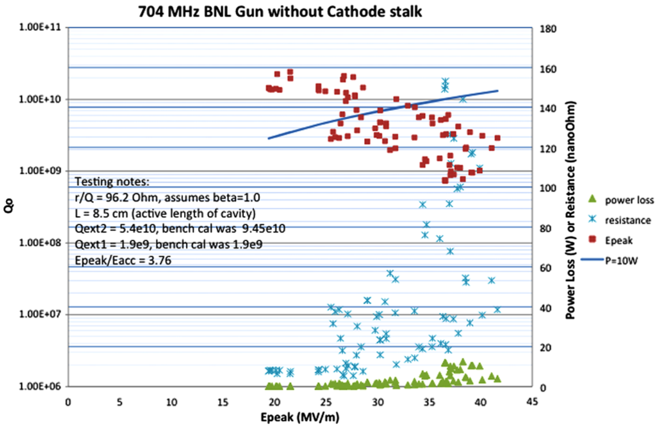

FIG. 8. Q_0 vs E measurements of the 704 MHz half cell BNL gun cavity without cathode stalk. Courtesy of Ilan Ben-Zvi, BNL.

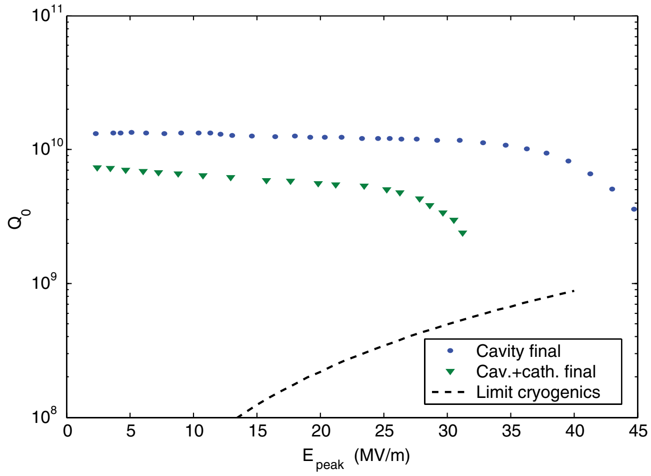

FIG. 10. Preliminary Q vs E_{peak} measurements of the 1.3 GHz 1.6 cell *BERLinPro* SRF gun. Courtesy of Axel Neumann, HZB.

this basic test, a 1.6 cell SRF gun with a NC cathode stem and a multialkaline cathode (CsK_2Sb) will be used to investigate high average current operation. The designed parameters for both cavities are listed in Table I.

Preliminary Q vs E_{peak} measurements, done in the vertical test bed at Jefferson Laboratory, show promising results (Fig. 10).

IV. NC CATHODE, DC GAP, AND SUPERCONDUCTING CAVITY

IHIP PKU, 1.3 GHz—3.5 cell DC-SC rf gun

In 2001 the development of a hybrid DC-SC rf photoinjector started at the Institute of Heavy Ion Physics of Peking University (IHIP PKU) [30]. This alternative approach to overcome the contamination difficulties consists of a 100 kV DC Pierce gun that is directly connected to a 1.3 GHz superconducting cavity. The Cs_2Te cathode is exposed to a DC electric field used for extraction and preacceleration of the electrons before they enter the boosting superconducting cavity through an 8 mm tube. The cutoff frequency of this tube is far above 1.3 GHz and thus the arrangement prevents rf induced losses and dark current at the cathode surface. It also reduces the risk of cavity contamination and makes a choke filter dispensable. Because of the somewhat low field gradient at the cathode, the beam quality achieved is slightly inferior to other SRF gun concepts. The first test with beam done in 2004 [31] proved the feasibility of the injector concept. But, to fulfill the requirements for the future PKU FEL an improved 3.5 cell cavity was designed (Fig. 11). The cavity made from large grain niobium successfully passed the vertical test at TJNAF (Fig. 12) and is ready for final assembly [32]. All parts of the cryostat including magnetic and LN_2 shielding, tuning system, input coupler, liquid helium vessel, and all supporting components are fabricated and ready for final assembly. Commissioning and first beam tests are planned in 2010 [33]. The expected injector parameters are listed in Table I.

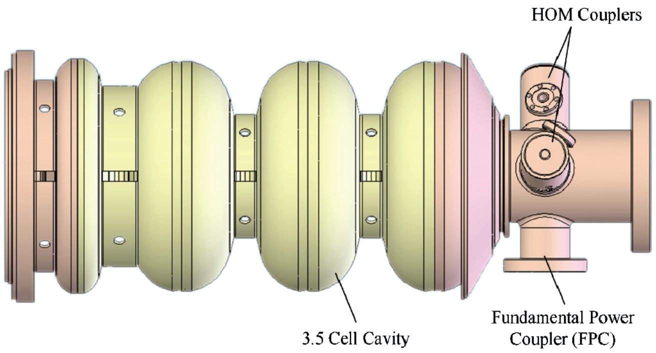

FIG. 11. 1.3 GHz—3.5 cell IHIP SRF gun cavity. Courtesy of Kexin Liu, PKU.

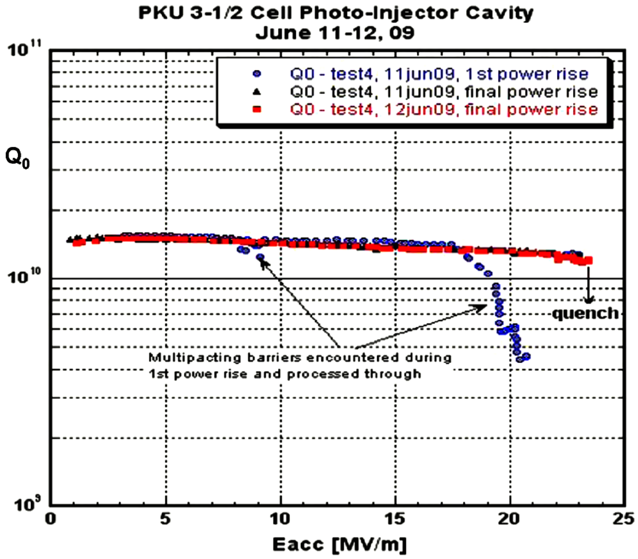

FIG. 12. Q_0 vs E_{acc} during vertical test measurement done at TJNAF. Courtesy of Kexin Liu, PKU.

V. NC CATHODE AND 1/4 WAVE SRF CAVITY

The most recent approach in the SRF gun community is the combination of quarter wave SC cavities and NC cathodes. Figures 13–15 show the three quarter wave guns with frequencies between 112–500 MHz. These guns are under development at the Brookhaven National Laboratory (BNL), the University of Wisconsin (UW), and the Naval Postgraduate School (NPS), respectively. The cavity geometry allows for a desired low frequency while maintaining reasonably small size. This results in the following advantages: (i) relaxed cryostat helium temperature requirements [cryoplant is operated at 4.2 K (surface resistance scales with f^2)]; (ii) reduced rf losses at the cathode surface [dielectric loss $\sim f$, skin effect $\sim \mathrm{sqrt}(f)$]; (iii) reduced wake field losses and wake field induced emittance growth [$W_{\parallel} \sim f$, $W_{\perp} \sim f^3$]; (iv) high transit time factor due to the short acceleration gap length compared to the rf wavelength ($\lambda/30$ to $2\lambda/15$); (v) high power rf sources and rf couplers available and tested up to 800 kW at 500 MHz CW.

Multipacting has been shown not to be a critical issue in these structures as long as good processing is performed and good operating vacuum is maintained.

At recent cavities electric peak fields of up to 100 MV/m at magnetic fields of about 200 mT can be achieved at a liquid helium temperature of 1.8 K. For 4.2 K helium temperature, the maximum field strength was estimated to be at least half that value. In all projects, the cathodes are placed at the end of the inner conductor where the electric field is largest. In addition, cavity and cathode are isolated from each other to allow its room temperature operation. In contrast to the complicated choke filters mentioned in both approaches before, the low frequency allows simpler quarter wave filters.

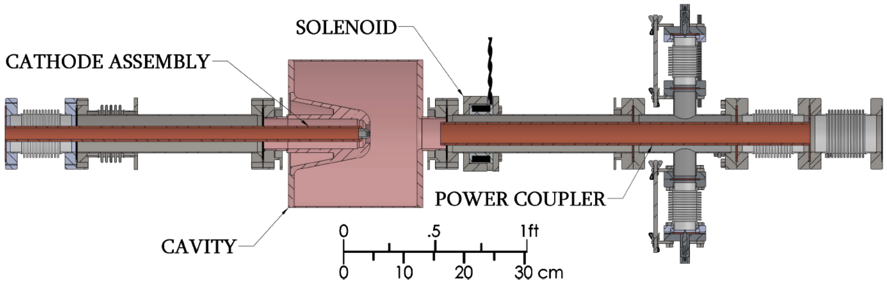

FIG. 13. 500 MHz—quarter wave NPS SRF gun cavity string. Courtesy of Terry Grimm, NIOWAVE Inc.

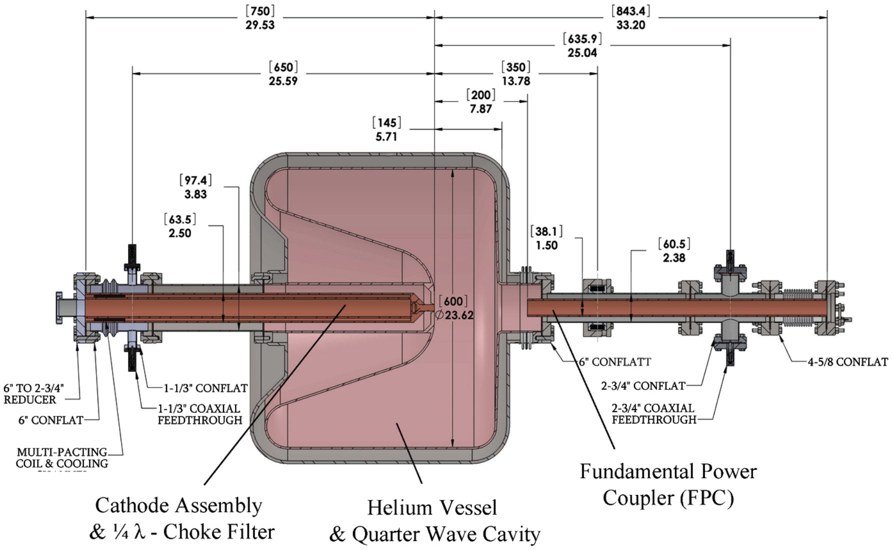

FIG. 14. 200 MHz—quarter wave Wisconsin University gun cavity. Courtesy of Terry Grimm, NIOWAVE Inc.

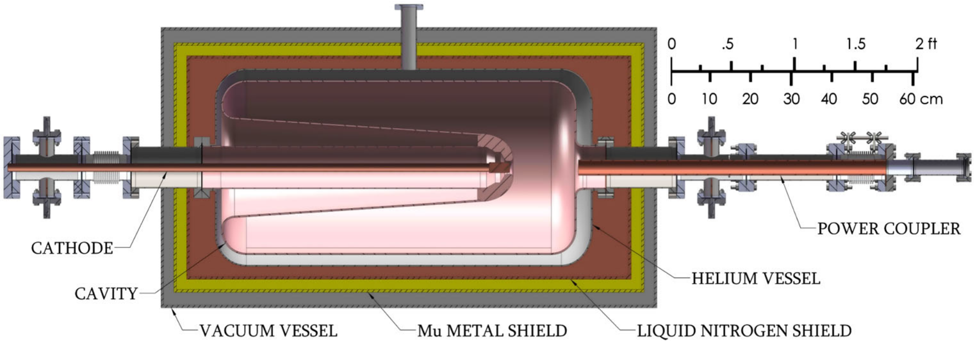

FIG. 15. 112 MHz—quarter wave BNL SRF gun cavity string. Courtesy of Terry Grimm, NIOWAVE Inc.

For emittance compensation the use of superconducting solenoids placed at the exit of the gun as well as cathode recess are discussed. Simulations of all three guns have shown their capability to generate nC bunches with high brightness necessary for applications such as FELs and high energy electron coolers.

A. NPS 500 MHz—quarter wave SRF gun

NPS is currently developing a superconducting linac as part of their test facility for ERL FEL research [34]. This test bed is based on two Stanford-Rossendorf accelerator modules and a 500 MHz quarter wave SRF photoinjector [35]. The gun string is shown in Fig. 13.

Besides the typical components mentioned before, the NPS gun is equipped with an axial beam pipe rf coupler to reduce dipole kicks. This coupler is adjustable and allows for good higher order mode damping. The NPS gun development is in an advanced state. The module design is finished and a SC solenoid as well as a prototype cavity was fabricated by Niowave Inc.

The assembled gun was cooled down to 4.2 K and first initial tests were done. Experimental results are assumed to be available in the fall of 2010. The beam parameters listed in Table I are the final goal. They may be not achievable with the present prototype cavity. The choice of the photocathode may not yet be final. Future developments include coupling the quarter wave cavity to additional cells, study of high power input couplers with higher order mode extraction, as well as cathode research using different electron emitters (photo, thermionic, field emission, and secondary). Also the use of multiple mode (multiple frequencies) operation for focusing and bunch length control is planned to be explored.

B. Wisconsin University 200 MHz—quarter wave SRF gun

The University of Wisconsin–Madison, the Synchrotron Radiation Center, and the Massachusetts Institute of Technology (MIT) are presently designing a seeded VUV/soft x-ray free-electron laser serving multiple simultaneous users. The present design uses an L-band CW superconducting 2.2 GeV electron linac to deliver 200 pC bunches to multiple FELs that are operating at repetition rates from kHz to MHz [36]. An important part of this project is the prototyping of a CW superconducting rf photoinjector operating in the self-inflating bunch mode. Bunches are produced by a photocathode using a laser pulse of about 30 fs duration with a hemispherical transverse density distribution. The "charge pancake" produced by the laser pulse then expands under space charge forces to an ellipsoidal bunch with constant charge density ("blow out" mode [37,38]). At the end of this process, bunch peak currents of 50 A with less than 1 mm mrad normalized transverse slice emittance are anticipated. The gun is designed to provide multimegahertz pulse repetition rates.

The blow out mode requires a continuous electric field of about 40 MV/m at the cathode. To meet this requirement a 200 MHz superconducting quarter wave structure is proposed (Fig. 14). Besides the cavity the design also includes the axial beam line coupler and a superconducting solenoid. The normal conducting cathode stalk is electrically and thermally isolated using a rf choke and a thermal gap, respectively [39].

The low frequency offers the advantage of a very flat field profile in the accelerating gap and thereby introduces less rf curvature on the bunch energy profile than an L-band device would do. This approach is less sensitive to errors in the drive laser timing. Furthermore, the lower magnetic to electric peak field ratio allows electric fields of about twice the value obtainable in elliptical cavities.

Additionally, the design is attractive because of its 4.2 K operation mode and the lower rf currents circulating in the cathode region that allows a simpler load lock and rf choke design. The parameters of this gun are summarized in Table I.

C. BNL 112 MHz—quarter wave SRF gun

Besides the elliptical cavity approach to design a high-current SRF gun for electron cooling at RHIC, BNL is also working on a quarter wave version to produce long electron bunches [40,41]. In this low frequency concept, even for high bunch charges, space charge effects can be kept small and an electron beam of the required quality can be provided to the cooling section. A prototype of such a 112 MHz SRF gun (Fig. 15) is presently under construction by Niowave Inc. in Michigan (see also [8]).

The project is part of DOE's Small Business Innovation Research and designed to be a proof-of-principle experiment to demonstrate the 4.2 K gun technology as an application for low energy electron cooling. Preliminarily, a gun exit energy of 2.69 MeV and a "beer can" laser size of $R = 5.5$ mm, $L = 11.0°$ (270 ps, 8.14 cm full length) is proposed for 5 nC bunch charge. More injector parameters are given in Table I.

VI. SUPERCONDUCTING CATHODE AND ELLIPTICAL SRF CAVITY

The technological difficulty of all three types of approaches mentioned before is the integration of a non-superconducting cathode with its limited lifetime into a superconducting cavity. The cathode itself and also the complicated procedure for the cathode exchange increase the risk of cavity contamination. This problem triggered the idea to realize the cathode as a layer on the cavity back itself. Niobium or another superconducting metal, e.g., lead, could allow an "infinite" lifetime and no load lock or choke system would be needed any longer. First investigations at BNL measuring the photoemission from bulk niobium resulted in QE $< 10^{-5}$ at 266 nm. Since this value is too small, in 2005 the concept of a Pb/Nb hybrid SRF injector was proposed. This option makes use of a superconducting lead cathode [42].

1.3 GHz—1.6 cell Pb/Nb hybrid SRF gun

DESY, BNL, the Stony Brook University, TJNAF, the Institute for Nuclear Studies (INS) in Poland, and Stanford Linear Accelerator Center (SLAC) collaborate to build a hybrid Pb/Nb SRF photoinjector with a lead spot as electron emitter. Lead is a common superconductor often used in accelerator technique. The critical temperature is $T_C =$ 7.2 K and not very different from niobium. The photoemission properties of lead have been studied extensively in the past [43]. These results make lead an attractive option for moderate average current sources. The best measured QE between 0.2%–0.3% at 213 nm would require 2.1 W laser power to generate an average beam current of 1 mA. As concerns lead coating, arc deposition seems to be the optimal method. Modest laser cleaning of the background is sufficient to achieve maximum QE without damaging the lead coating. Figure 16 illustrates a

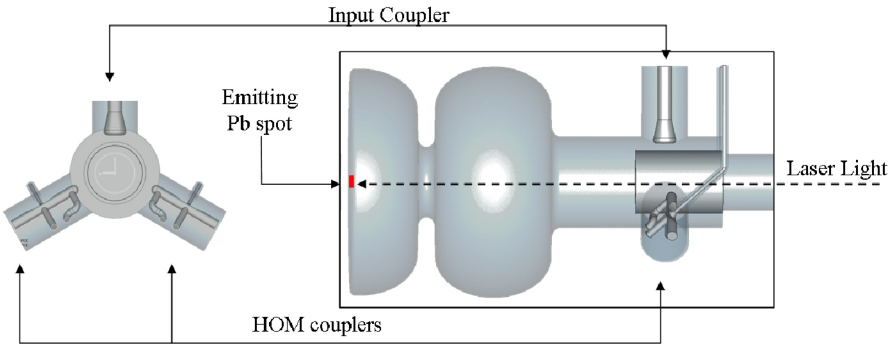

FIG. 16. 1.3 GHz—1.6 cell Pb/Nb hybrid SRF gun cavity. Courtesy of Jacek Sekutowicz.

proposed 1.6 cell low loss hybrid Pb/Nb gun design. The emitting lead spot (Ø < 3 mm) is located in the back wall center of the cavity. The coupler section is equipped with two HOM couplers, one input coupler and a pickup probe. In order to reduce transverse kicks a coaxial inset is planned [44]. A solenoid installed directly at the cavity exit will be used for emittance growth compensation. All expected parameters are listed in Table I.

Baseline tests using two half cell resonators were done to measure the lead QE at 2 K. The rf performance of these hybrid cavities is reported in [45]. In order to improve lead coating and cavity cleaning, two further half cell and one 1.6 cell TESLA cavity were built additionally.

The cathode depositions for these cavities were done by the Soltan Institute using a mask for shielding the whole inner wall of the cavity except for the cathode spot position. After the coating the lead spot itself needs to be protected from the acid of the cavity treatment procedures by another mask. The preparation and the vertical tests took place at TJNAF. During the first vertical tests after lead coating, Q disease at all three cavities was observed. The hydrogen in the air intestinally dissolved in the heated niobium wall during the lead plasma deposition. Later tests, using an improved lead deposition technique, showed that the performance of both half cells was still not satisfactory, whereas the 1.6 cell cavity achieved 46 MV/m without significant Q degradation (Fig. 17).

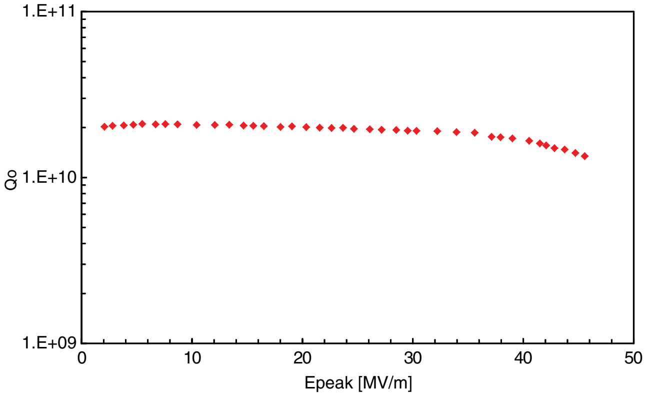

FIG. 17. Vertical test result of the 1.6 cell hybrid gun cavity with lead spot. Courtesy of Jacek Sekutowicz.

Further investigations of this gun type include detailed studies of the coating process, the intrinsic Q and QE variation during laser irradiation as well as the coaxial coupling. A common goal with the BESSY group is the generation of an electron beam for emittance measurements in 2010 [46].

VII. SUMMARY

Initiated by the success of the FZD in 2002, lots of SRF gun projects were advanced in recent years throughout the world. These differ from each other depending on the intended application in both the shape and the number of cavity cells as well as in the type of cathodes. A comparison of the sources, in particular, with respect to beam characteristics, is difficult because each is a compromise between the requirements and the technical feasibility. For some the focus is on a high average power while others pursue more moderate currents with good emittance at high bunch charge.

An attempt to present all electron sources despite their different parameters in one chart is to use the bunch brightness B. As shown in the following equation, it is defined as the ratio of peak current $\hat{I}$ and the product of the two normalized transverse emittances $\varepsilon_{n,t}$:

$$B = \frac{2\hat{I}}{\pi^2 \varepsilon_{n,x}\varepsilon_{n,y}}. \qquad (1)$$

The peak current of a Gaussian bunch follows from the ratio of bunch charge and bunch length (FWHM). Both the emittance and the peak current are determined by the combination of accelerating field strength and laser pulse.

In Fig. 18, the brightness of all SRF guns (red squares) as a function of the average current is shown. All required parameters are taken from Table I. Based on the distribution, a trend can be seen, describing deterioration in beam quality with increasing average current. This is caused by technological limitations of the available lasers and cathodes as well as rf couplers and rf sources. For instance, the limited power of rf couplers and amplifiers reduces the

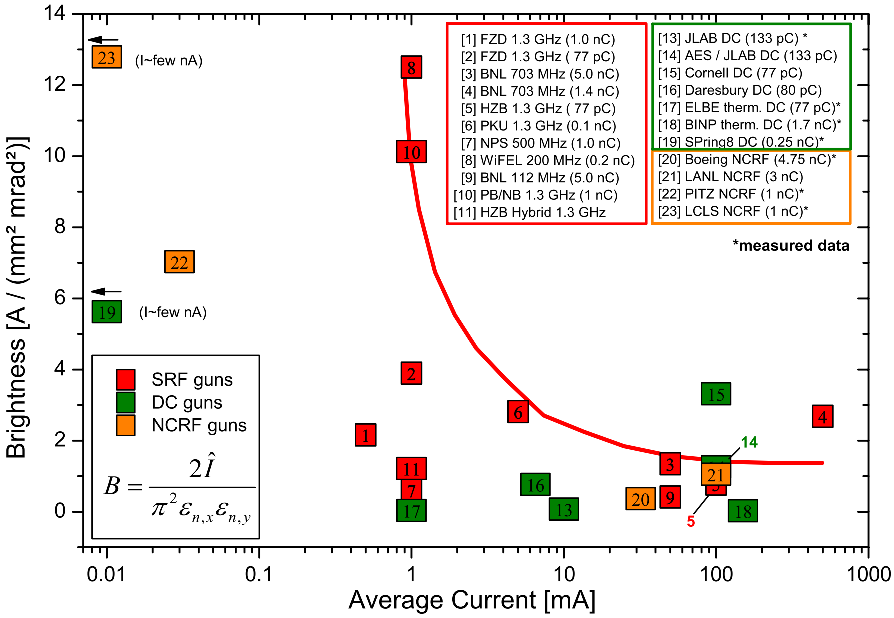

FIG. 18. Comparison of some electron sources by plotting bunch brightness versus average current. The colored squares are representing the three types of guns. An anticipated trend for SRF guns is shown by the red curve.

available energy gain at growing beam currents. For this reason, high-current SRF guns usually consist of one or two cells and deliver not more than moderate emittances, especially at short bunches with a high charge (see BNL/AES). An improvement can be achieved by reducing the bunch charge. In this case, the brightness remains approximately unchanged but the average current is limited by the available rf frequency (see HZB).

The same is true for quarter wave cavities. In comparison to elliptical cells, they cannot be paired easily with each other and therefore they are limited to one cell. However, the availability of suitable couplers and rf sources at low frequencies allows high beam power up to 1 MW. In addition, the longer oscillation period allows high bunch charge just by extending the bunch length. In this case a bunch compressor is additionally needed. An exception is the WiFEL gun, but one has to wait whether the blow out mode will work in the planned manner. Nevertheless, a current upgrade to more than 1 mA is difficult because this would require a multi-MHz laser with high peak and high average power.

By the way, the same is true for the low QE cathode of the PB/NB hybrid gun.

As of today, the planned sources of WiFEL, Pb/Nb, BNL and HZB determine the boundary of the technical feasibility. This is qualitatively indicated by the red curve in Fig. 18. Conservative designed sources include a safety margin and thus are situated below the curve. The FZD gun, for example, might be capable to deliver up to 5 mA (limited by the rf coupler) while the limit of the NPS gun is anticipated to be at 500 mA or above.

For further comparison, the chart was expanded by the DC and NCRF high-current sources summarized in [47] and the three existing high brightness injectors of Spring8 [48], Flash [49], and Linac Coherent Light Source [50]. All parameters refer to the exit of each injector. Fields marked with (*) are measured values, while all others are taken from design reports. Today, the best high brightness sources demonstrate very high beam quality at least for low currents. Its increase is possible, but only at the expense of bunch brightness. All existing sources (Boeing, JLAB, BINP) as well as the planned ones are lined up in the same area as the SRF guns. Remarkable in this context are the WiFEL and the Pb/Nb gun. Both are planned to deliver high brightness beams, only known from NCRF guns, but at much higher average current.

Besides the known technological challenges of DC and NCRF guns, the SRF guns have to deal with a superconducting cavity and its technologically sophisticated cryogenic clean room environment. Particular attention is focused on the interaction with the NC cathode. To date, the sole experience at Rossendorf does not show any degradation of intrinsic quality factor. However, two projects pursue alternative approaches to avoid the anticipated problems, but creating new ones elsewhere. The use of a SC cathode, for example, is causing difficulties in application and preparation of the lead spot as well as in obtaining the electric field (hybrid guns). A different approach at the PKU has to grapple with the problems of DC guns and for the same reason it is limited in the bunch charge.

All remaining projects, following the Rossendorf model, use either normal conducting Cs_2Te or CsK_2Sb cathodes. In both cases a choke filter is required, whereas at low frequencies a simple quarter wave structure might be sufficient. Nevertheless, for all guns these filters pose a problem in cleaning and assembly. So far, experiences are missing and the processing has to be done with extra care, because this important step decides whether a SRF gun project becomes a story of success or not.

Another little-studied problem is multipacting (MP) in the cathode region. In both the FZD and the elliptical BNL cavity hard MP barriers were experimentally found. To date only the FZD could overcome this issue. Results of all other projects are pending.

The last open point is the capability of the cathodes to deliver high average currents up to 500 mA, especially for a long time in a superconducting environment. Initial tests using a Cs_2Te cathode at FZD have shown an accumulated charge of 7 C over a period of 300 hours without any degradation of the QE. But this is still far away from the projected parameters.

In summary, it can be stated that many of the projects are progressing very quickly and that they are well advanced in a short time. Unexpected difficulties will lead to delays, but the SRF gun community is now unstoppable. To date, it is still open which approach is able to solve all problems and thus we may be curious about the first gun that demonstrates its specified beam parameters.

ACKNOWLEDGMENTS

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[1] C. Hermandez-Garcia, in *Proceedings of ERL09, Ithaca, NY, 2009* (Cornell University, Ithaca, 2009), WG102, p. 6; WG107, p. 37.

[2] D. H. Dowell *et al.*, Appl. Phys. Lett. **63**, 2035 (1993).

[3] H. Chaloupka *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **285**, 327 (1989).

[4] A. Michalke, Ph.D. thesis, University Wuppertal, 1992, WUB-DIS 92-5.

[5] D. Janssen *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **507**, 314 (2003).

[6] K. Flöttmann, D. Janssen, and V. Volkov, Phys. Rev. ST Accel. Beams **7**, 090702 (2004).

[7] J. W. Lewellen *et al.*, in Proceedings of ERL09, Ithaca, NY, 2009 (Ref. [1]), WG101; WG103, p. 24.

[8] A. Burrill, in Proceedings of ERL09, Ithaca, New York, 2009 (Ref. [1]), WG119; WG103, p. 24.

[9] M. Cole, in *Collaboration Workshop on RHIC Cooling and High-Brightness Electron Beams* (Brookhaven National Laboratory, Brookhaven, New York, 2006).

[10] V. Volkov *et al.*, in *Proceedings of RUPAC XX, Novosibirsk, Russia, 2006* (Budker Institute of Nuclear Physics, Novosibirsk, 2006), MOFP01.

[11] A. Arnold *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **577**, 440 (2007).

[12] A. Arnold, in *Proceedings of FEL06, Berlin, Germany, 2006* (BESSY, Berlin, 2006), p. 567.

[13] A. Arnold *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **593**, 57 (2008).

[14] P. Murcek *et al.*, in *Proceedings of SRF09, Berlin, Germany, 2009* (Helmholtz Zentrum für Materialien und Energie, Berlin, 2009), p. 585.

[15] A. Arnold *et al.*, AIP Conf. Proc. **1149**, 1125 (2009).

[16] R. Xiang *et al.*, in Proceedings of SRF09, Berlin, Germany, 2009 (Ref. [14]), p. 254.

[17] J. Teichert *et al.*, AIP Conf. Proc. **1149**, 1119 (2009).

[18] J. Teichert, in Proceedings of ERL09, Ithaca, New York, 2009 (Ref. [1]), JS303; WG103, p. 24

[19] R. Calaga *et al.*, in *Proceedings of SRF05, Ithaca, 2005* (Cornell University, Ithaca, 2005), THP20.

[20] R. Calaga, in Collaboration Workshop on RHIC Cooling and High-Brightness Electron Beams (Ref. [9]).

[21] I. Ben-Zvi, in *Proceedings of Electron Ion Collider Collaboration (EICC)* (GSI, Darmstadt, Germany, 2009).

[22] J. Smedley, in Proceedings of ERL09, Ithaca, New York, USA, 2009 (Ref. [1]), WG114; WG103, p. 24.

[23] J. Smedley *et al.*, in *Proceedings of MRS Fall Meeting, Boston, 2007* (Material Research Society, Boston, 2007), 1039-P09-02.

[24] A. Burrill, in Proceedings of ERL2007, Daresbury, UK, 2007, http://www.astec.ac.uk/ERL07/wg1.htm.

[25] I. Ben-Zvi *et al.*, in Proceedings of SRF09, Berlin, Germany, 2009 (Ref. [14]), p. 41.

[26] R. Calaga *et al.*, Physica (Amsterdam) **441C**, 159 (2006).

[27] M. Abo-Bakr *et al.*, in Proceedings of SRF09, Berlin, Germany, 2009 (Ref. [14]), p. 223.

[28] T. Kamps *et al.*, Rev. Sci. Instrum. **79**, 093301 (2008).

[29] T. Kamps *et al.*, in Proceedings of SRF09, Berlin, Germany, 2009 (Ref. [14]), p. 164.

[30] R. Xiang *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **528**, 321 (2004).

[31] J. Hao *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **557**, 138 (2006).

[32] S. Quan, F. Zhu, and J. Hao, Phys. Rev. ST Accel. Beams **13**, 042001 (2010).

[33] K. Liu, in Proceedings of ERL09, Ithaca, New York, 2009 (Ref. [1]), JS301; WG103, p. 24

[34] J. W. Lewellen *et al.*, in Proceedings of FEL08, Gyeongju, Korea, 2008 (Pohang Accelerator Laboratory, Pohang, 2009), p. 394.

[35] J. W. Lewellen *et al.*, in Proceedings of LINAC08, Victoria, BC, Canada, 2008 (Triumph, Victoria, 2009), p. 495.

[36] J. Bisognano *et al.*, in *Proceedings of the 23rd Particle Accelerator Conference, Vancouver, Canada, 2009* (IEEE, Piscataway, NJ, 2009), MO4PBC04.

[37] R. Legg *et al.*, in *Proceedings of the 11th European Particle Accelerator Conference, Genoa, 2008* (EPS-AG, Genoa, Italy, 2008), MOPD012.

[38] O. J. Luiten *et al.*, Phys. Rev. Lett. **93**, 094802 (2004).

[39] R. Legg, in Proceedings of ERL09, Ithaca, New York, 2009 (Ref. [1]), WG118; WG103, p. 24.

[40] A. Fedotov *et al.*, BNL Collider-Accelerator AP Note: C-A/AP/307, 2008.

[41] A. V. Fedotov *et al.*, in Proceedings of COOL2009, Lanzhou, China, 2009 (IMP CAS, Lanzhou, 2010), MOM2MCIO01.

[42] J. Sekutowicz *et al.*, TESLA-FEL Report No. 2005-09, DESY, 2005.

[43] J. Smedley, T. Rao, and J. Sekutowicz, Phys. Rev. ST Accel. Beams **11**, 013502 (2008).

[44] J. Sekutowicz and P. Kneisel, in Proceedings of the 23rd Particle Accelerator Conference, Vancouver, Canada, 2009 (Ref. [36]), TU5PFP053.

[45] J. Sekutowicz, in *Proceedings of the 2007 Particle Accelerator Conference, Albuquerque, New Mexico* (IEEE, Albuquerque, New Mexico, 2007), p. 962.

[46] J. Sekutowicz *et al.*, in Proceedings of the 23rd Particle Accelerator Conference, Vancouver, Canada, 2009 (Ref. [36]), MO6RFP056.

[47] A. Todd, Nucl. Instrum. Methods Phys. Res., Sect. A **557**, 36 (2006).

[48] H. Tanaka *et al.*, in Proceedings of FEL06, Berlin, Germany, 2009 (Ref. [12]), p. 769.

[49] F. Stephan *et al.*, Phys. Rev. ST Accel. Beams **13**, 020704 (2010).

[50] R. Akre *et al.*, Phys. Rev. ST Accel. Beams **11**, 030703 (2008).