SRF GUN DEVELOPMENT OVERVIEW

J. Sekutowicz, DESY, Hamburg, Germany

Abstract

The most demanding component of a continuous wave (cw) operating electron injector delivering low emittance electron bunches is the cw operating RF-gun. RF-guns, both working at room temperature and superconducting, particularly when they generate highly populated low emittance bunches have to operate at high accelerating gradients to suppress space charge effects diluting emittance. Superconducting RF-guns (SRF-guns) are technically superior to normal conducting devices because they dissipate orders of magnitude less power at very high gradients in the cw mode. In this contribution, progress made since the SRF13 conference in R&D programs, designing and operation of the SRF-guns at KEK, HZB, HZDR, PKU and DESY is discussed.

INTRODUCTION

SRF-guns have a potential to generate low emittance electron beams, if required with highly populated bunches, when operating in cw mode at high accelerating gradients. This makes the superconducting RF-guns superior to the room temperature operating devices, which at high gradients, operating in cw mode, would dissipate an enormous amount of RF-power. The main motivation for the development of and application for the SRF electron sources are facilities generating coherent photon beams. In general, the anticipated use is two-fold, Energy Recovery Linacs (ERL) and FEL facilities. In the past years, two directions in R&D programs could be observed. The first is meant for ERLs are SRF sources generating very high current electron beams whose bunches are rather low populated and whose repetition rate is high. The second are low current SRF electron sources, devoted mainly to FELs, whose bunches have higher charge but whose repetition rate is low, as compared to the ERLs electron sources.

The difficult part of all SRF-gun designs is the integration of a cathode into a clean superconducting (sc) cavity. This is especially challenging when a cathode is non-metallic, which is the case for all high quantum efficiency (QE) emitting materials commonly used in high beam current electron sources.

Three SRF-gun design approaches are under investigation since more than a decade:

- DC Pierce gun adjacent to sc cavity.
- Choke filter with a non-superconducting cathode.
- Superconducting cathode integrated into sc cavity.

The main advantage of the first approach is that the cathode does not penetrate the interior of the sc gun cavity, which helps to preserve its SRF performance. The main limitation is that low energy emitted electrons must pass certain distance before they enter the high electric accelerating field of the sc cavity. This constrains emittance of the beam and/or electron population per bunch due to the space charge force. The approach has been investigated for many years at Peking University (PKU).

The second approach is superior to two others when high beam current is required for the cw operation of an accelerator. It utilizes a choke filter allowing employment of high QE, usually alkali cathodes, which are exposed directly to the accelerating field of a gun cavity. This enables achievement of low emittances even though the electron population per bunch is large. High QE makes requirements on the irradiating laser less demanding, permitting operation with lower pulse energy and at longer wavelength (fewer conversion stages). The QE and lifetime of an alkali cathode depend strongly on the vacuum in a gun. When the vacuum is good the best performing cathodes can operate for several months but even these have to be exchanged when QE drops below the spec. Detachable cathode plugs and load lock mechanisms, similar to those used for room temperature RF-guns, are attached to superconducting gun cavities to enable cathode exchange. Unfortunately, this limits RF performance of sc gun cavities and/or very often causes multipacting in the cathode vicinity. This type of SRF-gun operates successfully at HZDR and is there and at HZB and KEK under continuous development.

The third approach, meant for low and very low current beams, employs superconducting cathode material. Since ca. 10 years R&D program is ongoing at DESY with support of other laboratories to integrate into the sc environment and maintaining of QE of Pb-layers deposited on various versions of Nb cathode plugs. The implementation of a sc cathode material significantly simplifies the SRF-gun design but does not make problem-free the integration itself.

In the following, the progress in all above-mentioned projects is discussed in more detail.

R&D AT PKU

The PKU SRF-gun R&D program goal is a cw operating injector for the planned ERL facility, whose final electron energy and beam current will be 30 MeV and 1 mA correspondingly. Figures 1 and 2 show a picture of the 3.5-cell SRF cavity and a drawing of the DC Pierce gun with cavity. Table 1 displays goal and achieved parameter for the PKU electron gun. There was remarkable progress in the project over the last two years demonstrated by the recent results shown in the table. The large grain Nb gun cavity without cathode in the final vertical test has reached E_{acc} of 23.5 MV/m with intrinsic $Qo>1\cdot10^{10}$, after two multipacting barriers had been conditioned. The reached E_{acc} is higher than the goal operational gradient of 13 MV/m required for the nominal electron energy of 5 MeV. Later, during the beam test both the DC voltage and cavity gradient were set to ca. half of their nominal spec values. Nonetheless, the normalized emittance of 2 µrad for 30 pC bunches measured at 162.5 kHz bunch repetition rate was very close to the goal value of 1.7 µrad. The QE of used in the test the Cs_2Te cathode for 266 nm wavelength was 4% at the beginning and 2% at the end of the test, and was considerably higher than its specified nominal value. The irradiating laser system performance also met the specification, both in the pulse energy E_γ and pulse duration. More details for the recent progress in the PKU project can be found in [1-3].

Figure 1: 3.5-cell 1.3GHz PKU cavity. *(Courtesy PKU)*

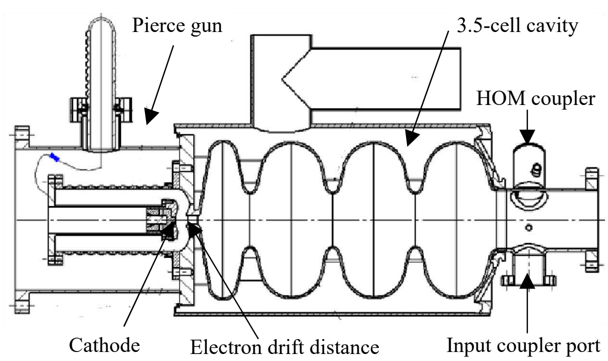

Figure 2: Drawing of DC Pierce gun and 3.5-cell PKU gun cavity. *(Courtesy PKU)*

Table 1: Goal and Measured Parameters at PKU

	Unit	Spec	Test
Bunch charge	pC	20	6~50
Bunch length	ps	1~3	1~3
Bunch rep. rate	MHz	81.25	0.1625 ; 81.25
Pulse / cw	-	Pulse	Pulse
RF-pulse duration	ms	5~10	7
Bunch shape	-	Gaussian	Gaussian
Trans. emittance	µrad	1.7	2.0
Long. emittance	Deg·keV	3.0	Not measured
Energy	MeV	5	3.4
Beam current	mA	1	0.55
QE at 266nm	%	>1	>2
Cathode life time	h	-	>150
E on cathode	MV/m	5	2.6
Eγ on cathode	nJ	12	12
Conv. efficiency	%	2	2
Laser pulse length	ps	5	5
Spot size (rms)	mm	1	1
Dark current	nA	-	<1

SRF-GUNS AT KEK, HZB AND HZDR

All three SRF-gun projects, discussed in this section, use or will use high QE non-superconducting emitting materials, deposited on a cathode stalk. They represent the second approach to the SRF-gun design discussed in the previous section.

SRF-gun at KEK

The KEK R&D SRF-gun program was initiated recently. The goal is an electron injector delivering high quality beam to the 3 GeV KEK ERL facility. The facility will operate in two modes with 100 mA and 10 mA electron beam. The goal parameters of the injector are listed in Table 2. Figure 3 shows a cross-section and a picture of a 1.3 GHz 1.5-cell prototype cavity, which unlike the proposed final version of the gun cavity, is equipped with only one input coupler. The final cavity will need two fundamental power couplers sharing very high input power the cavity will impart to the 100 mA electron beam. Two main challenges could be identified in this project; an integration of a bi-alkali cathode in the sc cavity and handling of 200 kW input power. The prototype cavity was recently tested without cathode stalk. It was the first vertical test from a series of five. The result of the test was very encouraging with respect to the achieved gradients. The cavity reached surface peak (E_{sp}) field of 66 MV/m (see Figure 4), 50% higher than the anticipated value listed in the table, corresponding to

Table 2: Key Parameters of SRF-gun at KEK

	Unit	Spec1	Spec 2
Bunch charge	pC	77	7.7
Bunch length	ps	3.2	3.2
Bunch rep. rate	MHz	1300	1300
Pulse / cw	-	cw	cw
Bunch shape	-	Gaussian	Gaussian
Trans. emittance	µrad	1.0	0.3
Long. emittance	neV·s	6.0	2.0
Beam current	mA	100	10
Energy	MeV	2	
QE at 520nm	%	3	
E on cathode	MV/m	25	
Eγ on cathode	nJ	6	
Laser pulse length	ps	10	
Spot size (rms)	mm	2	
Max. E on wall	MV/m	42	
Input power	kW	200	

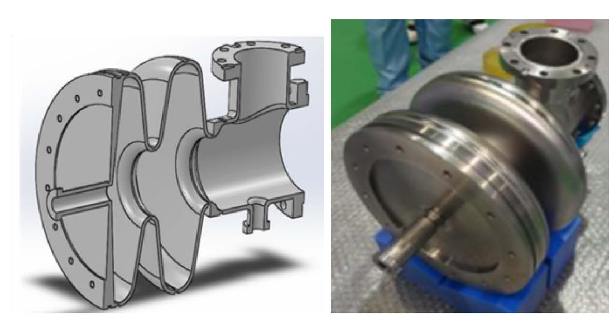

Figure 3: 1.3GHz prototype KEK cavity. *(Courtesy KEK)*

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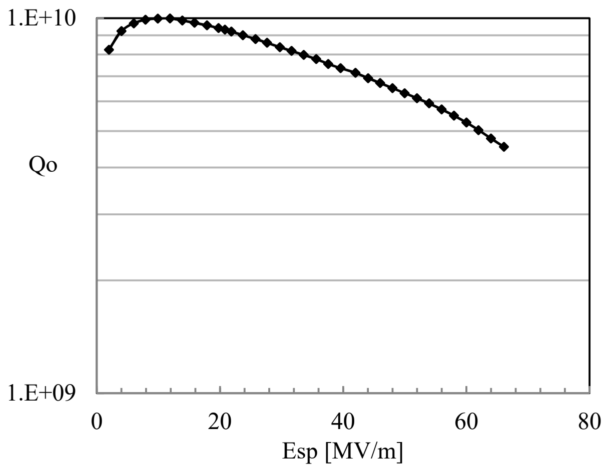

Figure 4: Qo vs peak surface field Esp measured at KEK in the first test at 1.7 K.

the nominal operational cathode field of 25 MV/m [4]. The test was conducted at a low temperature of 1.7 K, for which one would expect higher value of the intrinsic quality factor Qo. The test result indicates that an additional surface treatment may be advantageous.

In the next coming four vertical tests, the 1.5-cell cavity will be modified stepwise and will be equipped with additional parts, which will allow investigation of the design complexity:

- Test#2: Cavity + cathode rod
- Test#3: Cavity + choke cell (w/o inner conductor)
- Test#4: Cavity + choke filter + cathode rod
- Test#5: Cavity + choke filter + cathode rod + transparent cathode irradiated from the back.

Test No 2 is scheduled for September this year.

SRF-gun at HZB

The ongoing R&D SRF-gun program at HZB is an inherent part of the Laboratory project bERLinPro, which will be a 50 MeV ERL, operating with a beam up to 100 mA beam. The project funding was approved in 2010 and the conceptual design report was published in 2012 [5].

The SRF-gun goal parameters are displayed in the last column of Table 3. The 1.3 GHz sc gun-cavity in the HZB design is 1.4-cell long (see Fig. 5).

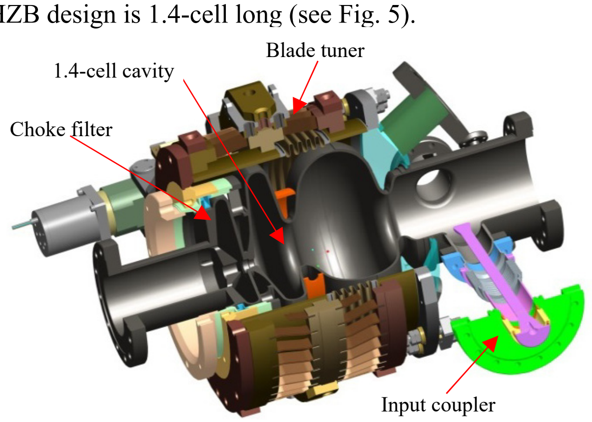

Figure 5: HZB SRF-gun structure equipped with a blade frequency tuner and an input coupler. *(Courtesy HZB)*

Similar to the KEK design, the structure will have two coaxial input couplers transmitting 230 kW of RF-power to the nominal 100mA beam. At first TTF3 couplers will be used, which in the final gun version for the operation in bERLinPro will be replaced with coaxial couplers designed at KEK. A choke filter will be attached to the 0.4-cell to avoid RF-power leakage. The bi-alkali CsK_2Sb cathode QE at 515 nm is assumed to be > 1%, and its lifetime longer than 7 days. The nominal electric field on the cathode will be 24 MV/m, allowing generation of 77 pC bunches with emittance in the range between 0.5-1.0 µrad. A load lock mechanism attached to the cavity will be used to exchange the cathodes.

Table 3: HZB Parameters for SRF-gun

	Unit	GunLab	Final version
Bunch charge	pC	0-100	77
Bunch length	ps	2-10	4.6
Bunch rep. rate	Hz	$10\text{-}10^4$	$1.3\cdot 10^9$
Pulse / cw	-	cw	cw
Bunch shape	-	Gaussian	Gaussian
Transvers emittance	µrad	0.4-10	0.5-1.0
Energy	MeV	1.2-3.5	2.3
Energy spread	keV	2-40	3
Beam current	mA	<0.04*	100
Input power	kW	20	230
E on cathode	MV/m	14-34	24
Max. E on wall	MV/m	26-61	45
Emitting material	-	CsK_2Sb	
QE at 515nm	%	1	
Cathode life time	day	>7	
Eγ on cathode	nJ	400@258nm 200@515nm	20@515nm
Laser pulse length (FWHM)	ps	3-4@258nm 4-16@515nm	4.6
Spot size (rms)	mm	0.1-1.5	0.5

*Administrative limit for the GunLab test stand.

The first prototype of the HZB gun cavity was built and tested several times in a vertical cryostat at TJNAF. Later, the cavity was tested at HZB. In all these experiments, the cavity was tested without cathode and cathode stalk.

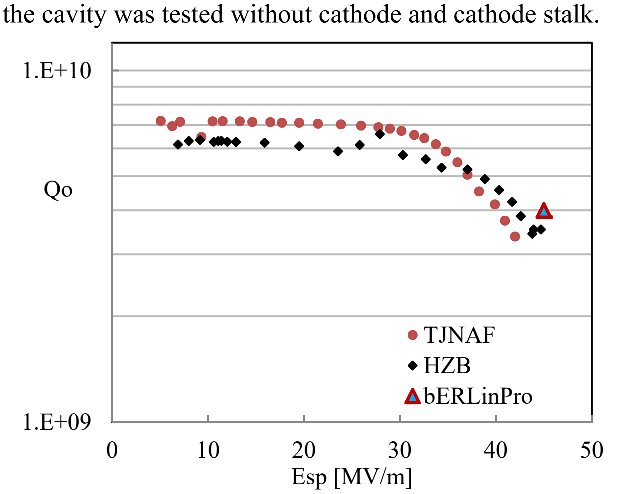

Figure 6: Qo vs peak surface field Esp as measured in vertical cryostat at TJNAF and at HZB at 1.8K.

Figure 6 shows the finally measured at TJNAF relation Qo vs peak surface field Esp and the same data remeasured later in the HZB horizontal cryostat HoBiCaT. The tests were performed at 1.8K. The diagram shows that the cavity slightly missed the bERLinPro spec (marked with tringle). The next HoBiCaT test of the first prototype, which for this test will be equipped with the TTF3 coupler, blade tuner, solenoid and a HOM beam line absorber is scheduled for this fall.

A second prototype of the gun cavity was ordered recently at industry. It will be assembled in a new cryostat and similarly will be equipped with components needed to operate the injector in bERLinPro, i.e. a sc solenoid, beam tube HOM absorber, a warm beam line diagnostic and the cathode exchange load lock unit (see Figure 7). The assembly of that cryostat will also begin this fall. The cryostat will be installed at the GunLab test stand. The operational parameters of the experiments at GunLab are displayed in the third column of Table 3. For these experiments, the cavity will be equipped with two TT3-type input couplers, whose RF-power capacity is limited to 10 kW per coupler. The beam current in GunLab will be limited to 40 µA by the irradiating laser 10 kHz repetition rate and the administrative radiation limit. The tests at GunLab will begin in summer 2016. More detailed information on the progress in the HZB R&D SRF-gun program can be found in [6–8].

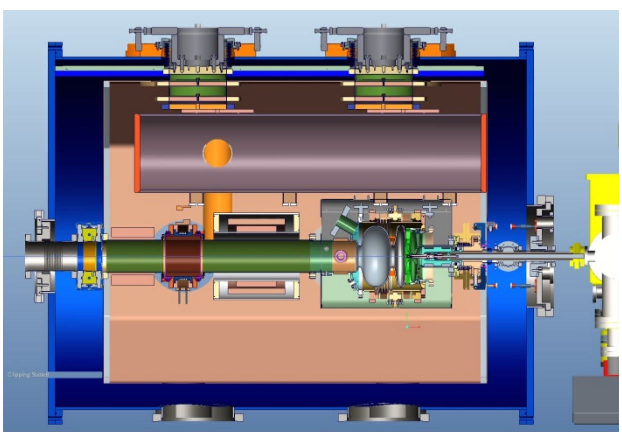

Figure 7: CAD view of the HZB SRF-gun structure assembled in a cryostat. *(Courtesy HZB)*

SRF-gun at HZDR

The SRF-gun program for the ELBE facility at HZDR is the most advanced among all programs worldwide. The ELBE gun is designed to operate in two modes, the FEL mode with charge per bunch <80pC at a high repetition rate of 13MHz and high charge mode with 1nC bunches at lower repetition rate of 0.5 MHz. The key target parameters for the FEL mode and those demonstrated up to now are listed in Table 4. Table 5 displays goal parameters for the high charge mode. The R&D program began in late 90', and has been continued since then providing many technical solutions, often adopted in other SRF injector projects. In April 2013, first lasing at ELBE was demonstrated with the electron beam delivered by Gun1, whose core element was the 1.3 GHz 3.5-cell sc niobium cavity with an attached choke filter. The Gun1 operation parameters are listed in Table 4. While many operation goal parameters were demonstrated, like bunch rep. rate, QE, laser pulse length…, several of them were not, e.g. final beam energy, bunch charge and emittance. Nevertheless, the Gun1 experiment was the milestone for many projects proving feasibility of the SRF guns application for FEL facilities. Few years before the Gun1 experiment took place, a second similar cavity, Gun2, had been ordered, built and then extensively vertically tested at TJNAF. After Gun2 was shipped to HZDR, the tests continued, this time in a horizontal cryostat. Figure 8 summarises the Gun2 cavity test results at TJNAF and HZDR. The data for Gun1 is included for comparison. The most successful Gun2 vertical test at TJNAF, without cathode, proves that one can reach significantly higher gradients with this cavity than with Gun1. Although the performance was worse in the horizontal test with attached Cu cathode (August 2014), Gun2 was still significantly superior to Gun1. The first operation period for ELBE began in June 2014 and ended in February 2015. During that run the gun delivered a 10nA beam at an energy of 3MeV and 100 kHz bunch repetition rate. The last horizontal test was conducted in May this year; unfortunately, after an unsuccessful insertion of the Cs_2Te cathode had caused severe contamination and degradation of the cavity.

Table 4: Goal and Measured Parameters for the FEL mode

	Unit	Spec	Test / Operation	
Gun#			Gun1	Gun2
Cathode	-	-	Cs_2Te	Cu
Bunch charge	pC	77	up to 400	3
Bunch length	ps	2		2
Bunch rep. rate	MHz	13	up to 13	0.1
Pulse / cw	-	cw	cw	
Bunch shape	-	Gaussian	Gaussian	
Trans. emittance	µrad	1.0	3@80pC	0.3
Energy	MeV	9.5	3.5	4.5
Beam current	µA	1000	400	0.1
QE at 258nm	%	1 (Cs_2Te)	1	0.002
Cathode lifetime	year	>1	0.24	NA
Max. E on cathode	MV/m	30	9.6	16
Eγ on cathode	nJ	40-500		
Conv. efficiency	%	10		
Laser pulse length	ps	3ps@13MHz		10ps@0.1MHz
Spot size (rms)	mm	0.5-4		

Table 5: Goal Parameters for the High Charge Mode

	Unit	Spec
Cathode	-	Cs_2Te
Bunch charge	nC	1
Bunch length (rms)	ps	10
Bunch rep. rate	kHz	500
Pulse / cw	-	cw
Bunch shape	-	Gaussian
Trans. emittance	µrad	2.5
Energy	MeV	9.5

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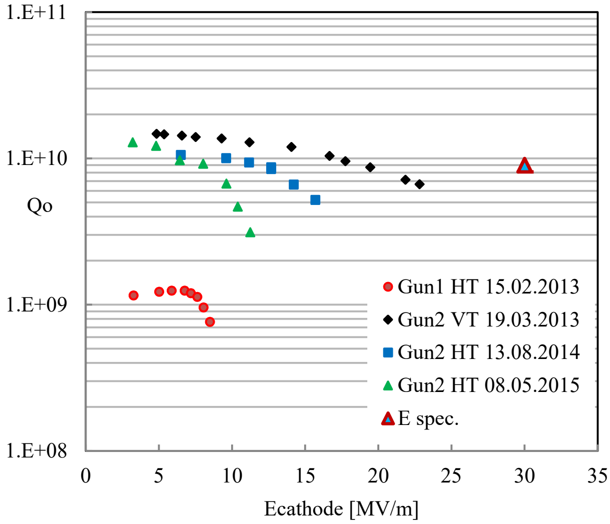

Figure 8: Tests results for Gun1 and Gun2 at TJNAF and at HZDR.

Currently, Gun2 operates at ELBE with a reduced peak cathode field of 11.2 MV/m. Even though the present performance is limited, the computer modelling showed that the gun is useful for the operation. The parameters up to now demonstrated (not simultaneously) of Gun2 in previous tests and during the operation are listed in the last column of Table 4. Figure 9 shows a cross-section of a cryostat housing the fully equipped Gun2 with the Cu cathode, solenoid, cold tuner and input coupler as it is now installed for operation at ELBE.

It is worth to note that a successful functionality test of the cold tuner used for Gun2 was done in 2014. The demonstrated tuning range was 275 kHz and 650 kHz for the cavity half-cell and full-cell respectively. The measured mechanical resolution was 1.25 nm/step, which corresponds to a frequency resolution of 0.8 Hz/step for the half-cell and 0.31 Hz/step for the full-cell. No hysteresis was observed for the half- and full-cell in the range of ±600 steps. The conclusion from the test was that performance of the cold tuner fulfilled the spec.

The present main goal for the HZDR team is an improvement in the integration of the Cs_2Te cathodes into the clean sc Gun2 without degradation in the cavity performance. More details can be found in [9-11].

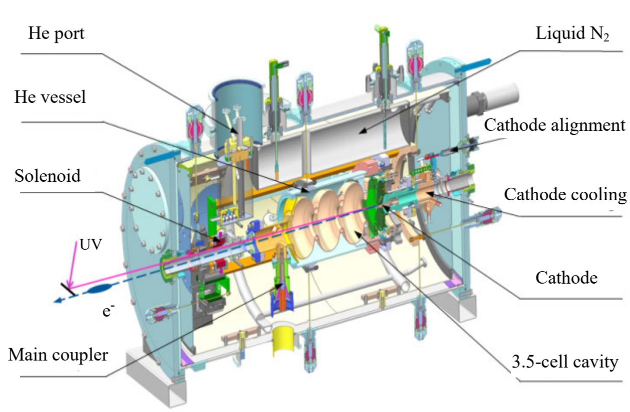

Figure 9: CAD drawing showing a cross section of the equipped Gun2 assembled in a cryostat. *(Courtesy HZDR)*

SRF-GUN R&D PROGRAM AT DESY

The superconducting electron injector program at DESY is motivated by the perspective of increasing flexibility in the time structure of FLASH and EXFEL photon beams by enabling long pulse and cw operation modes, in addition to the nominal short pulse (sp) operation. The all-superconducting RF-gun proposed at DESY employs a superconducting cathode simplifying the gun design, but whose moderate QE limits the beam current to a fraction of a mA. The program began in 2004, and since then enjoys acceptance and financial support of DESY authorities but can have only limited support because the DESY resources are since several years entirely devoted to the construction of the European XFEL facility, which is the highest priority accelerator project at the Laboratory. Some European financial support (EUCARD and EUCARD2), and the involvement of BNL, TJNAF, NCBJ, HZDR and a 3-year support of HZB, made possible the advancement of the program to the status presented here.

The goal parameters of the SRF-gun have been revised recently and became less critical as compared to the original parameters defined at the beginning of the project. The revision was made mainly due to the experimental proof at LCLS (SLAC) that the SASE process can take place with charges well below 1nC/bunch. Another argument was the wide spectrum of experiments described in the scientific case for the LCLS II laser, which nominally will operate in cw mode with 100 pc bunches delivered to undulators at 100 kHz repetition rate. Additionally, to increase the redundancy of FLASH and EXFEL, the SRF-gun will be a complementary electron source to a room-temperature photo-injectors delivering higher populated bunches, up to 1nC, during the nominal operation of these facilities.

The current target parameters of the DESY SRF-gun are listed in Table 6. A significantly lower charge per bunch 100 pC (previously 1 nC) and a lower repetition

Table 6: Goal Parameters of DESY Gun

	Unit	Spec
Cathode	-	Pb
Bunch charge	pC	100-300
Bunch length	ps	3
Bunch rep. rate	kHz	100-33
Pulse / cw	-	cw
Bunch shape	-	Gaussian
Trans. slice emittance	µrad	< 0.7@100pC
Energy	MeV	3.7
Beam current	µA	10
QE at 260nm	%	0.015
Cathode lifetime	Year	> 1
Max. E on cathode	MV/m	40
Eγ on cathode	µJ	2.4-7.2
Laser P at 260nm	W	0.24
Laser P at 1032	W	24
Optical efficiency	%	1
Spot size (rms)	mm	<1

rate of 100 kHz (previously 1 MHz) led to a much less demanding spec for the irradiating laser, whose required UV power on the cathode is 0.24 W. With the conservative assumption of 1% overall optical efficiency for the conversion to fourth harmonics and for the photon transport, ca. 24 W power laser will be needed at IR. Several goal parameters have been already demonstrated experimentally.

Cavity Performance

Figure 10 shows a drawing of the 1.6-cell DESY gun cavity prototype. The cavity is based on the 1.3 GHz TESLA/XFEL accelerating structure. The final version of the cavity will have two HOM couplers, which are not attached to the prototype. The cavity has an installed cathode plug, which is sealed to the back wall of the 0.6-cell with indium gasket. The plug (see Fig. 11), and cavity are made of high RRR niobium. For the base line test, the plug stays uncoated. In the latest version of the cathode plug, several channels for the liquid helium were milled to facilitate its better cooling. Figure 12 shows a picture of an insert with the prototype cavity prepared for the vertical test. In 2014 and 2015, three vertical tests were conducted. In recent tests frequent Q-switches were observed, from which the cavity could recover when it was warmed up above the Nb critical temperature. The result of the last two tests is shown in Figure 13.

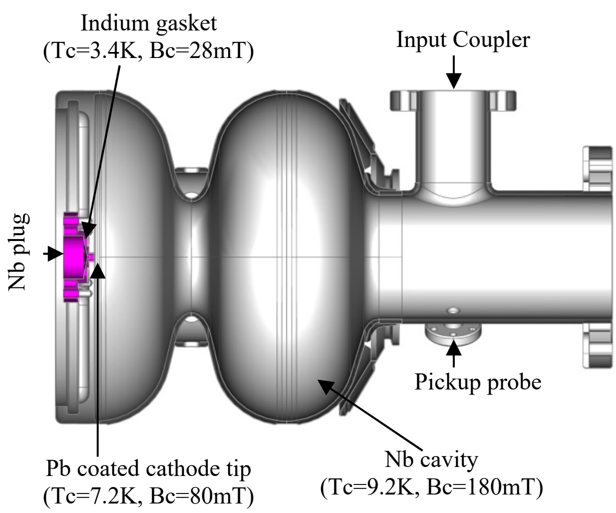

Figure 10: CAD drawing of the 1.6-cell DESY SRF-gun cavity with Nb-plug. Critical temperatures and magnetic flux for superconductors are shown in parenthesis.

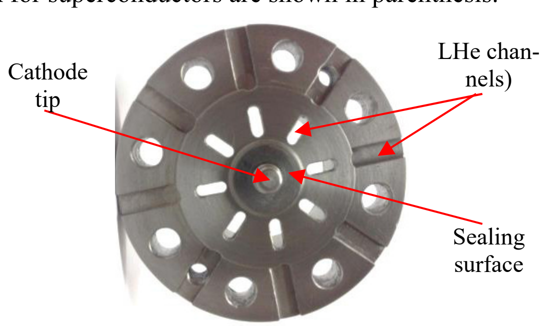

Figure 11: Nb cathode plug.

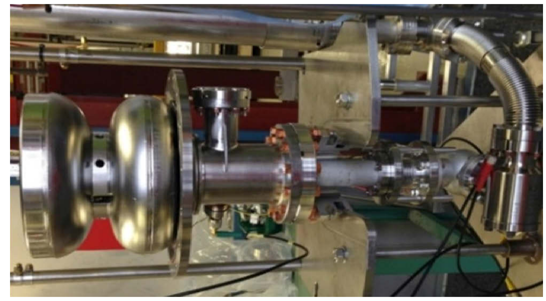

Figure 12: Prototype cavity in an insert, after electropolishing and high-pressure water rinsing, prepared for the vertical test.

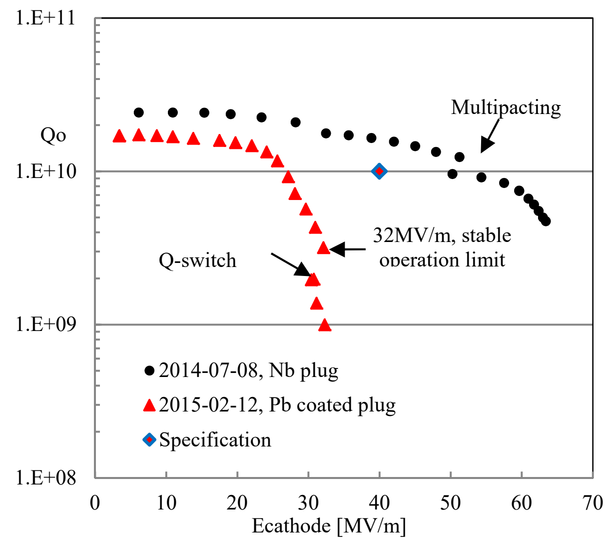

Figure 13: Recent test results for DESY SRF-gun cavity with the coated and uncoated plug. The shown multipacting could be processed in a short time.

The baseline test with the uncoated Nb-plug was very successful. The cavity reached 63 MV/m on the Nb cathode, well above the spec value of 40 MV/m. With the Pb-coated plug, the performance was worse. The cavity did not meet the spec. The operation was stable for gradients up to 32 MV/m. Qo at this gradient was very low, only $3 \cdot 10^9$. At 32 MV/m the Q-switch degraded the performance further. As already mentioned the cavity always recovered after it had been warmed above the niobium Tc. One possible explanation for the frequent Q-switches during the last tests is a much thicker indium gasket used for the plug assembly. For the very first assembly a 120 µm thick indium foil was sufficient to get the cavity vacuum tight. In the recent assembly, the gasket was ca. 1 mm thick due to deformation of the cavity back wall. This hypothesis will be proven in the coming test in September, for which the back wall was re-shaped to its original form.

QE of the Pb Cathode

One of the new plugs was Pb coated in July this year at NCBJ and then shipped to BNL for the QE test. John Smedley and his group perform the test which is still ongoing. The first obtained data is already available. The

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diagram in Figure 14 summarizes the BNL result. The measured QE for the Pb cathode as delivered is, as expected, very low. At 260 nm QE was $5 \cdot 10^{-7}$. After the first laser cleaning (1000 pulses with energy density of 0.6 mJ/mm^2), QE increased to $1.5 \cdot 10^{-4}$, which is the project target value. The second cleaning (10000 pulses with the same fluence) enhanced QE further by a factor of two, to $3 \cdot 10^{-4}$. The test confirmed that the laser cleaning, removing oxides and impurities from the surface, is crucial for lead cathodes. The tested Pb layer is ca. 18 µm thick. It was prepared with the arc-deposition method. Following the deposition, the layer was exposed to several argon plasma shots, which made the surface smoother, but still the obtained few micrometres roughness is too large if the cathode shall deliver very low emittance beams. Figure 15 displays pictures of the whole Pb cathode with mask after the plasma treatment and its central fragment (230 x 230 µm) after the laser cleaning. The droplets shown on the left photograph have diameters up to 100 µm but their elevation is few microns. The right photograph shows the roughness and sharp tips, which may cause emission of a dark current for very high gradients achievable with this gun. It is planned to melt the surface of this thick layer with a laser in vacuum to improve the smoothness. The process is scheduled for late September. After the melting, the QE test will be repeated. More data on the R&D program at DESY can be found in [12-15].

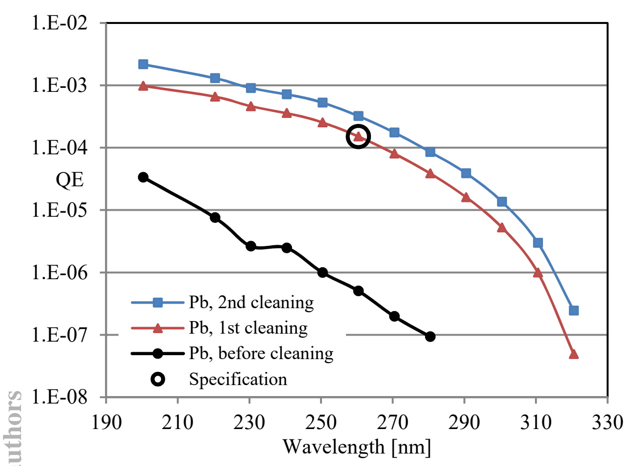

Figure 14: QE test results for of the Pb-layer deposited on the niobium plug at NCBJ. *Courtesy BNL*

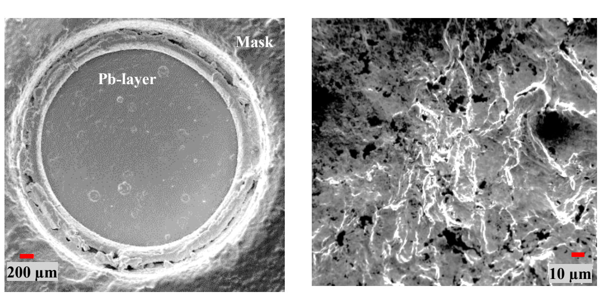

Figure 15: Pictures (not to scale) of the Pb-layer after the plasma treatment (left) and after the laser cleaning (right). *Courtesy NCBJ and BNL*

CONCLUSION

There is a remarkable progress in the SRF-gun R&D programs over the last two years, especially at PKU and HZDR where the electron injectors are correspondingly almost read for or already in operation. The new project at KEK and the project at HZB are in progress too, which is demonstrated in the computer modelling, prototyping, testing and cathode production. The R&D program at DESY for a low current injector recently showed the highest gradients on cathodes and the goal QE for the superconducting metallic cathode. In this program in the near future, more attention will be paid to improve the quality and smoothness of the coatings.

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