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A NOVEL DESIGN OF A HIGH BRIGHTNESS SUPERCONDUCTING RF PHOTOINJECTOR GUN CAVITY*

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Abstract

Next generation electron facilities for research, medical and industrial applications are in need of electron sources that operate at high repetition rates of 1 MHz and beyond, with normalized beam emittances in the order of 1 π mm-mrad for bunch charges as high as 1 nC. We have started to optimize a novel high beam brightness superconducting RF (SRF) photoinjector gun cavity that may fulfill these requirements. The work has been funded in 2012 by the U.S. Department of Energy as part of its Small Business Innovation Research program.

INTRODUCTION

SRF photoinjector gun cavities (hereafter: guns) promise to provide low beam emittances at high repetition rates (up to CW). Such sources will blend in naturally with SRF cavity linac technology - significantly advanced in recent years to offer CW operation at ~20MV/m accelerating fields - to deliver unprecedented flexibility to vary beam pulse patterns and to generate both high peak and average beam brightness. These abilities outperform normal-conducting RF and DC guns making SRF guns ultimately desired sources for large and small-scale next generation electron facilities. These comprise for instance Free Electron Lasers, Energy Recovery Linacs and Inverse Compton Back-Scattering sources.

However, the few SRF guns built today have either not been designed to fulfill the demands described above or could not demonstrate yet the envisaged performance goals after assembly in the horizontal cryostat due to repetitive and/or prevalent operational limitations [1]. Multipacting (MP) and field emission (FE) are the usual limiting factors encountered. Technical and operational problems are mostly related to the photocathode implemented in the superconducting environment of the cavity. For photocathodes not being superconductors a thermal insulation from the superconducting cavity walls is required. In this case, the back wall of the cavity is opened and the cathode inserted on a stalk from the backside of the cavity. This assembly forms a coaxial line behind the gun with zero cutoff frequency. Hence it requires the use of a choke filter system to reject the accelerating mode from propagating in the coaxial line (unless the line is also used as power input coupler). Stubborn MP in the coaxial line is a well-known issue that has been encountered in SRF guns (e.g. BNL gun [2]) and needs to be addressed by design. Moreover, surface cleaning around the small cathode opening is delicate. This for instance has led to surface damages and an early onset of FE in the FZD gun [1], which uses a resonant choke filter cell behind the cathode opening.

The choice of the material of the photocathode is decisive as it not only influences the complexity of the gun design, but also determines the required photo laser properties such as wavelength and power. Semi-conductor materials (e.g. Cs_2Te, CsK_2Sb, GaAs) are used in favour of pure metals due to superior quantum efficiency (QE $\geq$ 1%). However, these materials yield only relatively short lifetimes, while the QE is extremely sensitive to contaminations requiring careful UHV handling and storage.

As proposed in the first half of the last decade ([3], [4]), a cathode exchange system would become obsolete if one could merely laser-illuminate a spot of the superconducting cavity back wall serving as a metal cathode of principally unlimited lifetime. Obviously, Nb has been envisaged first in all-niobium cavities [5]. Studies of the QE of Nb in dependence on several surface treatments were conducted, but the QE remains < 0.001% at UV laser light ($\lambda_r = 266$ nm), i.e. too low to extract 1 nC per bunch at desired high repetition rates with tolerable laser power. Moreover, one has to consider to keep the cathode spot superconducting ($T_c = 9.3$ K of Nb). Alternatively, Pb deposited on the Nb cavity walls ($T_c = 7.2$ K, critical flux density ~70 mT) has been considered in the following years (Nb/Pb hybrid cavities). It has been found that lead is suitable to be illuminated over a wider laser wavelength regime and with a QE up to 0.5%, which depends on the laser wavelength and the deposition method ([6], [7], [8]). Lead would therefore allow beam operation at medium average currents (~1mA, i.e. 1 nC @ 1MHz) with reasonable laser power. Consequently it has been considered attractive for the proposal of this work fulfilling the minimum requirements of a cathode for a high brightness source.

TECHNICAL APPROACH

We propose a novel SRF gun concept that allows scrutinizing several critical aspects. The major objective is to design a cavity that would operate reliably at high peak fields in the presence of a superconducting photocathode layer deposited on the Nb back wall of the first cell. A sustainable high field level ($E_{peak} \geq 50$ MV/m) at the cathode is the essential parameter to limit space charge forces and guarantee normalized emittances in the lower π mm mrad range at bunch charges in the nC range. Additionally, the proposed SRF gun aims for less surface

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damage vulnerability by providing easy post-production interior surface cleaning possibilities and direct deposition of the (Pb) photocathode layer on the back wall. This is facilitated by a fully demountable and replaceable back wall. The demountable back wall also allows accessing the cavity interior directly for visible inspection and further post-processing for a best-practicable recovery in case a performance-limiting surface damage/contamination would be encountered. This idea has led to the consideration of utilizing a TM_{020} Eigenmode field pattern in the first half cell of the SRF gun followed by (a) standard full cell(s) resonating in the TM_{010}-mode. The use of a TM_{020}-mode may have been considered for normal-conducting cavities in different contexts before, but is novel to SRF cavities to our knowledge. The principal design of a 1½ -cell SRF gun is shown in Fig. 1 depicting electrical (left) and magnetic field contours (right) in perspective (top) and rear view (bottom), respectively.

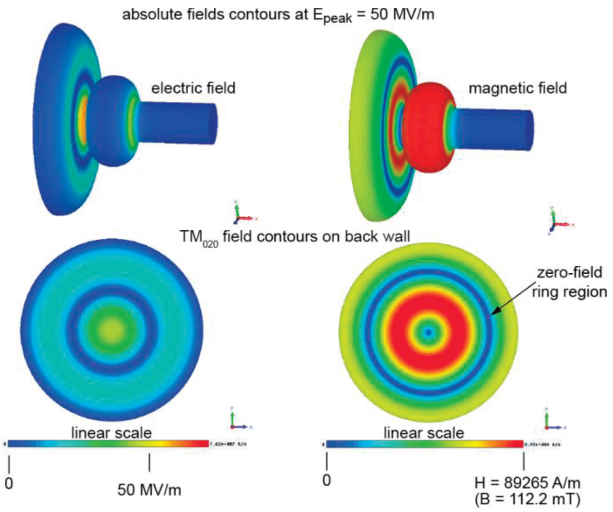


Figure 1: Electric (left) and magnetic field contours (right) in a 1.5 GHz SRF gun corresponding to 50 MV/m peak field at the photo cathode located at the center of the back wall (bottom).

The first half-cell needs to be larger in diameter such that the harmonic TM_{020}-mode resonates at the same frequency as the subsequent full cell(s) thereby providing a well-balanced on axis accelerating field profile. The crucial point is that the TM_{020} mode provides a zero magnetic field ring region off center. This feature grants to open the back wall quasi loss free such that a superconducting joint is possible. Compared to a conventional cavity design, the TM_{020}/TM_{010} gun stores a larger energy (U) in the first cell. This creates higher RF losses (P_{diss}) and therefore somewhat lowered characteristic shunt impedances (R/Q_0-value). However, since only the first cell is concerned, this drawback is not significant. The unloaded quality factor ($Q_0=\omega*U/P_{diss}$) is actually higher. A practical advantage is that the magnetic fields in the dome region are lower than in the second cell. Since the cavity is intended to be built by standard deep-drawing and electron beam-welding techniques, this helps to mitigate the losses in the heat affected weld zone. It may be beneficial to yield higher quench fields and therefore peak fields. In this way the TM_{020}-cell can also be designed to exhibit an unbalanced on-axis field profile, e.g. with the first cell sustaining a much higher peak field than the second cell. This could lower the transverse emittance. Fig. 2 (left) more clearly illustrates the magnetic field contours with a contour plot clamped to maximally 20 mT. It highlights the low magnetic field region ≤ 5 mT within a ring ~4 mm wide corresponding to a slope of 2.5 mT/mm in radial position for a cathode peak field as high as E_{peak} = 50 MV/m.

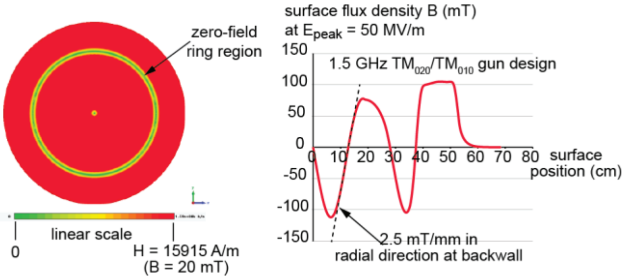


Figure 2: Left: Magnetic field contours at the back wall with fields clamped to maximally 20 mT (E_{peak} = 50 MV/m). Right: Surface magnetic flux density along the cavity contour starting at the cathode region.

One possible engineering solution with a flange/gasket connection is sketched in Fig. 3 for the 1.5 GHz gun chosen above. A hollow coaxial power input coupler can be positioned in the beam tube to avoid field asymmetries and related emittance increase. Note that the TM_{020}-mode in the first half cell has the potential to implement waveguide ports on the opposing side of the back wall, where the magnetic field also vanishes. Such openings are usually prohibited in SRF accelerating cavities. Thus the use of lower and higher order mode dampers, pickup probes or a laser port attached to the first half cell are viable options.

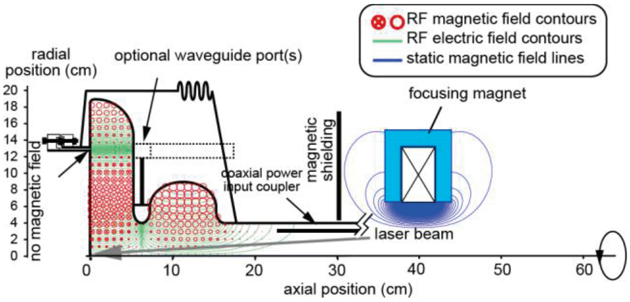


Figure 3: Principal TM_{020}/TM_{010} SRF gun cavity concept with demountable back plate. Dimensions are for a 1.5 GHz design.

With the back wall being demountable, a small circular coax line will be introduced inevitably. Though it resides at the minimum RF magnetic field, the electric field is at its local maximum. The dimensions of the gap need to be chosen properly to suppress possible MP per design within the operating field regime, while it is crucial to minimize RF losses of the residual fields leaking towards the flange/gasket connection. The cavity material will be high RRR grade niobium except the flange and gasket material. For instance, a conservative estimation shows that for a 3 mm gap between the demountable back plate and the cavity wall, a Q-degradation of ~15% would occur if the end of the line would be shorted with copper material at 20 K (non-superconductive), but a Q_0 in the range of 1e10 would still be feasible. Nevertheless, a superconducting joint is possible to avoid this Q-degradation. This requires the right material choice. In the past, superconducting connections have been pursued for cavity inter-connection beam tubes to gain real estate gradient in cryomodules. These attempts have sought to sustain a superconducting joint for flux densities as high as 30-40 mT resulting in partial success. In our case the demands are more relaxed. Indium routinely used as (demountable) gasket material has a critical quench field of ~15 mT. Several possible gasket and flange materials are available to facilitate the objective. Ref. [9] delivers valuable experimental data. Standard Nb55Ti flange material as used for SRF cavities for example have quench fields around 7 mT (but 200 smaller thermal conductivity than Nb at 2K), whereas Nb1Zr has been investigated to sustain fields up to 42 mT before quenching. NbZr is also available readily by industry. Moreover, nitridation is known to harden materials, such that NbN would serve well as flange material with good thermal properties. A nitrified Nb cavity reached a quench field of 65 mT [9].

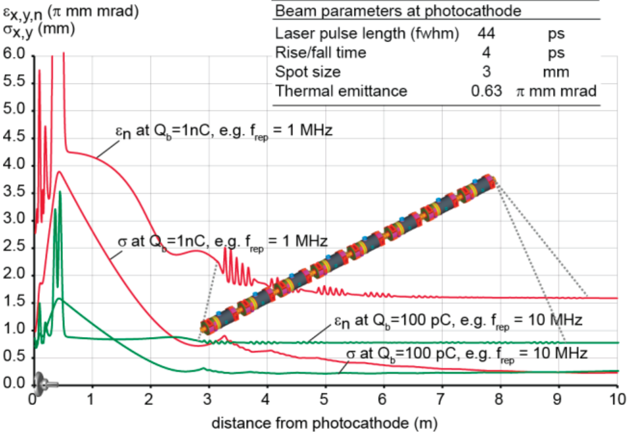
For the 1.5 GHz gun, the total power deposition in the niobium walls is ~12 Watts at $E_{peak} = 50$ MV/m. The power loss at the demountable back plate totals 2.1 W. This is still relaxed for a good thermal management at Helium temperature keeping the joint superconductive. Further gun parameters are summarized in Table 1.

Table 1: SRF gun geometrical and operational properties, here for 1.5 GHz. The gun is scalable to any frequency.

Parameter	Symbol	Units	Value
active length	L_{act}	cm	16.3
on axis peak field	E_{peak}	MV/m	50
beam energy after exit	E_b	MeV	4.8
accelerating field (E_b/L_{act})	E_{acc}	MV/m	29.3
surface resistance*	R_s	nΩ	21
unloaded quality factor*	Q_0		1.2e10
dynamic load	P_{diss}	W	12.1
char. shunt impedance**	R/Q_0	Ω	152
transit time factor**	TTF		0.83
stored energy	U	J	15.9
peak surface flux density	B_{peak}	mT	112

* assumed for Nb at 2 K, ** tracked particles from cathode to gun exit

Multivariate beam optimization results for two different linac setups are shown in Fig.4 conducted for the initial design above (1.5 GHz) with a flat back plate and $E_{peak} = 50$MV/m at bunch charges of 1 nC (red curves) and 100 pC (green curves), respectively. The plot presents the evolution of the projected normalized transverse rms emittance (ε_n) and rms beam size (σ) through the gun and one cavity cryomodule linac section. It demonstrates both the emittance conversation in the space-charge dominated regime, taking place in the drift space behind the gun, as well as emittance perseveration in a subsequent linac by proper matching. The beam can minimally - and ideally - possess the uncorrelated thermal emittance already generated at the photocathode. This portion can be significant. A thermal emittance of 0.63 mm mrad has been considered for this calculation.



Beam parameters at photocathode		
Laser pulse length (fwhm)	44	ps
Rise/fall time	4	ps
Spot size	3	mm
Thermal emittance	0.63	π mm mrad

Figure 4: Evolution of ε_n and $\sigma_{x,y}$ up to the exit of the 1st linac cryomodule as indicated for 1.0 nC (red curves) and 100pC (green curves), respectively (Astra calculations).

DISCUSSION AND OUTLOOK

As part of an SBIR Phase I program funded by the US Department of Energy we consider optimizing a novel TM_{020}/TM_{010} SRF gun with a demountable back wall. Present results for a preliminary design are already encouraging, but several aspects need to be addressed numerically including possible field emission and multipacting phenomena, the gun's mechanical stiffness as well as the thermal management. In collaboration with our partner institution SLAC, we will investigate most relevant physics using the massive parallel ACE3P suite of 3D Finite Element Analysis codes available at the National Energy Research Scientific Computing Center. Phase I aims to complete the work within one year and have ready a feasible engineering design of a gun that can be built and tested in a possible Phase II.

REFERENCES

[1] A. Arnold, J. Teichert, Physical Review Special Topics - AB 14, 024801 (2011).
[2] W. Xu et al., Proc. of PAC 2011, New York, USA.
[3] J. Sekutowicz et al., TESLA-FEL 2004-03.
[4] J. Smedley et al., Proc. of EPAC 2004, Lucerne, Switzerland, TUPKF080.
[5] T. Rao et al., BNL-73973-2005-CP, 2005.
[6] J. Smedley et al., Proc. of PAC 2005, Knoxville, USA, WPAP039.
[7] J. Sekutowicz et al., Proc. of EPAC 2006, Edinburgh, Scotland, THPLS092.
[8] J. Smedley et al., Physical Review Special Topics - AB 11, 013502 (2008).
[9] P. Kneisel et al., Proc. of the PAC 2007, New Mexico, USA, WEPMS062.