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SRF GUN DEVELOPMENT FOR AN ENERGY-RECOVERY LINAC BASED FUTURE LIGHT SOURCE

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Abstract

In this paper we describe the R&D roadmap at HZB for the development of a high-brightness, high average current SRF electron gun for an energy-recovery linac based synchrotron radiation source.

MOTIVATION

With the arrival of superconducting radio-frequency accelerators dedicated to the generation of synchrotron and coherent radiation in the form of energy-recovery linacs (ERL) [1, 2, 3] the demands on the sources that supply the electrons to the accelerators are becoming more and more stringent. The photon beam quality depends strongly on the ability of the electron accelerator complex to deliver an electron beam of exceptional quality. ERL operation requires high peak brightness at high duty cycle, high average current, and high beam parameter stability.

Helmholtz-Zentrum Berlin (HZB) suggests an ERL based light source as the successor to the Soft X-ray storage ring synchrotron radiation source Bessy II [4] currently in operation in Berlin. In order to demonstrate generation and energy recovery of a 100 mA average current and 1 mm mrad normalized transverse emittance beam HZB is proposing BERLinPro [1], a fully integrated ERL test facility including all major systems found in ERLs like electron gun, booster section, merger beamline, main linac, return loop and high power beam dump. For high flexibility, the electron source must also be able to generate pulses with bunch charges ranging from a few pC up to 1 nC with repetition rates from several MHz to GHz. Superconducting radio-frequency (SRF) injectors have the highest potential as electron sources to serve this incredible parameter range, as they are able to operate at 100% duty factor. Hence SRF systems can fulfill the ERL electron source requirements and provide for maximum flexibility. Most importantly, they offer the most potential for continued future improvements, so vital to the upgrade of ERL facilities.

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SRF GUNS

The development of SRF photo-electron guns, pioneered at Wuppertal University in 1991 [5], continues to make strong advances with several interesting projects currently underway (see [6, 7] for overviews). There are currently two main development lines, using elliptical and quarter-wave resonators for initial acceleration. The approach for BERLinPro and the future ERL at HZB is based on a derivative of the TESLA cavity philosophy, with an elliptical cavity design and operating frequency of 1.3 GHz.

There are many challanges to the successful operation of SRF guns as high-brightness, high average current electron beam sources. These combine aspects of SRF cavities with challenges related to high quantum-efficiency photocathodes and combination of both:

- Have a low risk cathode/ SRF cavity interface with vacuum shield and RF choke,
- Operate SC or NC cathode inside an SRF cavity with high accelerating field,
- Verify the emittance compensation scheme,
- Evaluate the solenoid location and effect on the SRF cavity performance,
- Design minimum beam-disruptive high power RF feeds for power levels above 100 kW,
- Evaluate the need and design of higher-order mode coupler,
- Achieve high cathode quantum-efficiency lifetime and develop a reliable and robust procedure for cathode preparation, transport and changing.

All these issues will be addressed with BERLinPro and the SRF gun tests at HZB. The R&D roadmap is layed out such that all major aspects are covered. The approach is staged, tackling one item after the other and rely where possible on promising ideas and existing solutions which meet the requirements for ERL operation.

ROADMAP AT HZB

The first stage of the development aims at the design of an all superconducting high brightness gun. This gun, shown in Fig. 1 contains a 1.3 GHz 1.5 cell gun cavity where the back wall has a small area coated with Pb, a superconductor, that is used as the photocathode. The goal of this program is to build a robust gun capable of operating below 1 mA average current, with 77 pC bunch charge and with a normalized emittance of 1 mm mrad. By utilizing the back wall as the photocathode the additional complications associated with introducing a normal conducting photocathode are avoided. The first milestone of the project, planned for spring 2010, is to perform RF measurements of the interaction between the SRF cavity and SC solenoid in the HoBiCaT [8] cryovessel. In the next step the drive laser and beam diagnostic devices will be added for first beam operation in autumn 2010.

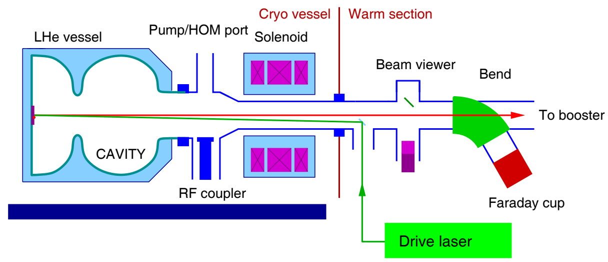

Figure 1: Conceptual design for an all SC electron souce.

For the next stage a SC gun cavity with NC cathode insert is foreseen. Then a CsK_2Sb cathode is required to reach also high brightness at high average current. In Table 1 the main parameters for the two guns are listed. The operating points for both guns are developed from beam dynamics considerations from an analytical model and code-aided parameter optimization.

Table 1: Parameters of the Roadmap Guns

Parameter	HoBiCaT	BERLinPro
Goal	Brightness	Current
Electron energy	1.5 MeV	
RF frequency	1.3 GHz	
Design peak field	50 MV/m	
Operation launch field	$\geq$ 10 MV/m	
Bunch charge	77 pC	
Repetition rate	30 kHz	$\leq$ 1.3 GHz
Cathode material	Pb	CsK_2Sb
Laser wavelength	258 nm	526 nm
Laser pulse energy	0.15 μJ	4 nJ
Laser pulse shape	Gaussian	Flat-top
Laser pulse length	2.5 ps	15 ps
Average current	0.5 μA	100 mA

OPERATING POINT

We chose 1.3 GHz for the frequency of the accelerating mode to be fully compatible with the RF infrastructure of the BERLinPro booster and main linac. The design of the gun cavity is derived from the TESLA cavity design, which is well understood and experimentally proven to provide a low E_{peak}/E_{acc} ratio, which is desirable for the accelerating cavity of a RF gun. The choice for the number of cells is a compromise between the requirements of an exit energy > 1 MeV and field on the cathode during extraction of > 10 MeV/m. First design studies [9] with a half-cell showed reasonable performance with respect to transverse beam quality due to the high gradient during extraction. Longitudinally the beam pulse cannot be compressed in a way to stop space-charge driven beam expansion. Adding one cell solves this problem. The starting point for the design is thus a cavity with 1.5 cells, where the full cell is of TESLA type and the half cell is designed such that it provides maximum field at the cathode location.

RF Coupler Limit

The RF input power coupler puts a limit on the RF field which the electrons experience during emission and thus sets limit for space-charge dominated emission. For the baseline design of BERLinPro it is assumed to use two Cornell-type coupler [10] which are able to guide each 75 kW of average RF power at 1.3 GHz to the cavity. Using two couplers 150 kW can be delivered to the cavity. For 100 mA average current, an exit energy of 1.5 MeV can be reached with this power level. Studies showed that with a maximum field of 36 MV/m a launch field of 25 MV/m can be created in a 0.6 cell cavity, while for the 1.6 cell cavity the maximum field is only 22 MV/m and the launch field 15 MV/m. The launch field sets the lower-limit for space-charge dominated emission.

Space Charge Limit

Space charge effects put a lower limit on the charge density which can be extracted from a cathode and thus for the thermal emittance. In the static approximation one can imagine that the photoelectrons from cathode form a pancake-shaped cloud in front of the cathode, which shields the electric field from the accelerating mode in the cavity. Acceleration stops when the space charge field equals the applied field. From the space charge limited beam radius the minimum achievable thermal (or cathode) emittance can be computed. In practise the space charge limit cannot be reached as the bunch length would increase such that longitudinal effects would increase the projected emittance. DC guns operate usually a factor two to three away from the space charge limit, while with RF guns it is possible to come very close to this limit. Playing emittance compensation, a unique feature for RF guns, enables operation of a gun close to this limit.

Including RF Effects

In addition to space charge forces and emission properties, the transverse emittance is also dominated by RF fields. The uncompensated emittance of Gaussian pulses can be modelled as the sum of squares of the thermal, RF and space charge emittance like $\varepsilon_{tot}^2 = \varepsilon_{th}^2 + \varepsilon_{RF}^2 + \varepsilon_{sc}^2$. The scaling of the uncompensated, beam dynamics plus thermal, emittance is derived in [12, 13], evaluated for two cases, with 77 pC and 1 nC, and shown in Fig. 2. RF guns perform best in the saddle region between space

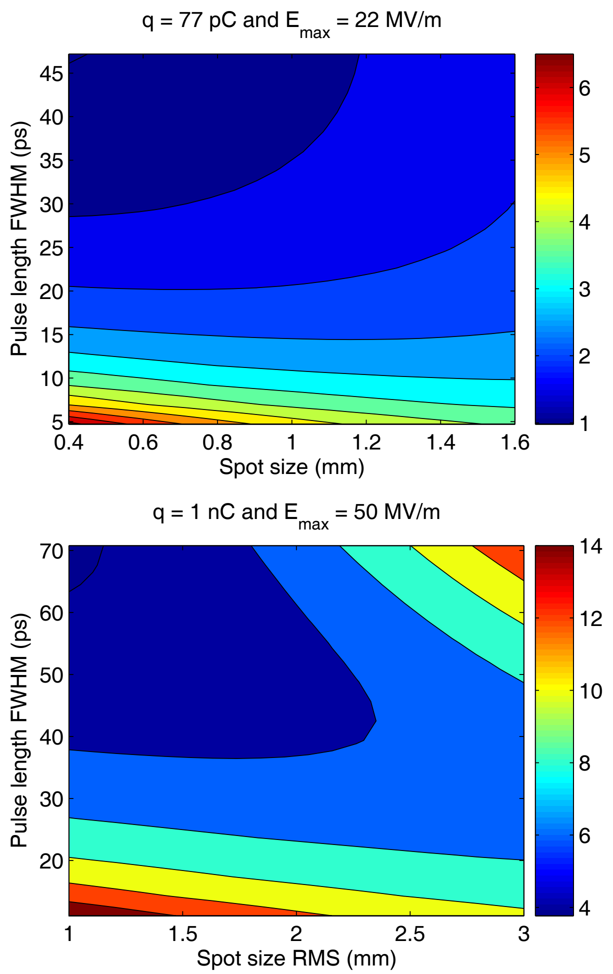

Figure 2: Analytical models for the uncompensated emittance for two gun scenarios. Space charge forces dominate the region for short pulses and small spot size, while RF effects dominate for long pulses and large spot sizes. Due to the higher gradient the emittance with 1 nC is more influenced by RF effects than the 77 pC case.

charge and RF dominated regimes. With emittance compensation, that is by placing a solenoid at appropriate distance from the cathode and subsequent acceleration in a booster linac, the emittance can be reduced by factor of two to three. Further improvement is achievable by illuminating the cathode with a truncated transverse distribution and flat-top pulse shape for the longitudinal direction of the drive laser pulse. The analytical model gives nonetheless a good starting point for gun design parameters. The final choice and performance studies have to be done with numerical simulations. Results of these studies using the ASTRA code [11] are shown in Fig. 3. These results will

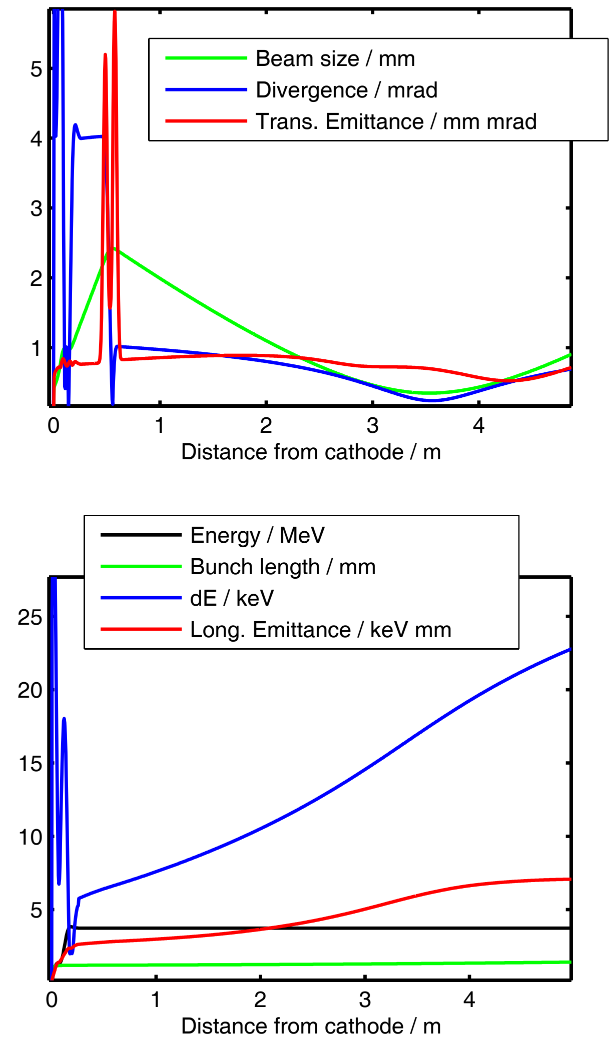

Figure 3: Performance studies with ideal (only rotational symmetric fields) for 77 pC bunch charge. The maximum field is E_{max} = 40 mV/m, the solenoid is located 0.53 m away from the cathode and has a B_o of 150 mT. The initial laser profile is round with a radius of 0.4 mm rms, and flat-top longitudinal profile with 2 ps edges and 15 ps plateau length.

be verified experimentally with the SRF gun tests at HZB.

CURRENT ACTIVITIES

SRF Cavity

To date a gun cavity with Pb cathode has been tested at Jefferson Lab in the vertical test area (VTA) and has reached 45 MV/m peak field with a quality factor Q of $1.0 \cdot 10^{10}$ [14]. Currently a gun cavity dedicated for the beam tests in HoBiCaT is under development. This cavity is similar to the cavity described in [14] with design changes related to the back wall of the first half cell. For the first beam test the aim is to keep the design of the LHe vessel as simple as possible and to operate the cavity without a tuner. After cooldown of the cavity LHe pressure fluctuations will lead to cavity back wall deformation, the back wall acts like a membrane. This back wall deformation will cause a frequency detuning. The range of this detuning has to stay within the bandwidth of the RF power source which is available at HoBiCaT. At HoBiCaT, pressure fluctuations of 0.1 mbar at 16 mbar pressure level are observed, causing a frequency shift of 86 Hz, which is larger than the bandwidth of 30 Hz. With a stiffening u-bar profile on the outside of the back-wall, the frequency shift can be reduced by a factor of three.

Photocathodes

The cryogenic environment of a SRF cavity places considerable constraints on the choice of the photocathode. Any material that is not a superconductor needs to be thermally insulated against the Nb surface of the SRF cavity. Thus the cathode material has to be applied to a stock, which reaches into an opening in the back wall of the SRF cavity and resembles an antenna, which can couple to the electro-magnetic field of the accelerating mode. A choke filter is this required to block leakage of RF power [15]. With this solution, any type of normal-conducting cathode developed for normal-conducting RF guns can be considered.

Another option is to use a superconductor as the cathode. This simplifies greatly the design of the back region. Lead (Pb) is a type I superconductor with a critical temperature of 7.2 K and critical magnetic field of 80 mT. The photoemission properties from Pb cathodes have been modeled and measured, both at room and at cryogenic temperatures [16]. At 260 nm (4th harmonic of YAG) the quantum efficiency is roughly $5 \cdot 10^{-4}$, at 213 nm (5th harmonic) already $1 \cdot 10^{-3}$. The back wall of the HoBiCaT gun cavity will be coated with a Pb film. With this approach we are able to tackle the issues relating to the generation of a high-brightnes beam, mitigating the issues related to the cathode/cavity interface to the next stage of the project.

For BERLinPro, the baseline cathode will be CsK_2Sb, due to the high QE at visible wavelengths [17]. For this reason, the setup of an advanced cathode preparation and characterization system is one the R&D roadmap for BERLinPro. Characterization of the cathodes will be done at the synchrotron radiation source Bessy II using material and surface science techniques such as XPS and ARPES. This development is critical to achieve high average current. We are planning to add a suitable cathode/cavity design to the BERLinPro gun, and perform tests with high QE cathodes.

Drive Laser

The commissioning of the mark 1 SRF gun requires only moderate bunch charges of a few pC. The commissioning-laser consits of a diode-pumped Yb:YAG oscillator with a diode-pumped regenerative amplifier. We want to use the fourth harmonic of YAG to operate the Pb cathode with 258 nm wavelength. The laser pulse length will be initially around 2.5 ps FWHM, with pulse energies in the order of $0.15\ \mu$J. The repetition rate will be 3 kHz, which can be reduced up to a factor of 255. The laser can be equipped with a pulse-strechter and additional amplifiers to reach nC bunch charges from Pb cathodes. For this pulse energies of up to $10\ \mu$J are necessary, raising the average power of the laser in the UV to 0.5 W. For the BERLinPro gun a fiber-based laser system is envisaged.

SC Solenoid

For emittance compensation a superconducting solenoid with NbTi coils will be placed close to the SRF cavity inside the cryovessel. The solenoid field shape and decay are important, especially in the direction of the SRF cavity. Therefore a design with compensation coils or a special flux return yoke is foreseen.

CONCLUSIONS

Performance studies indicate that a SRF gun is the appropriate choice to drive an ERL based synchrotron radiation source. The roadmap at HZB aims towards a fully operational electron source for BERLinPro.

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REFERENCES

[1] W. Anders, et al, Proc. of SRF 2009, Berlin, Germany, 2009.

[2] G. Hofstätter, et al, Proc. of ERL 2009, Ithaca, USA, 2009.

[3] G. R. Neill, et al, NIM A 557, 2006.

[4] E. Jaeschke, et al, Proc. of PAC 1997, Vancouver, Canada, 1997.

[5] A. Michalke, PhD Thesis, WUB-DIS 92-5 Univ. Wuppertal, 1992.

[6] J. W. Lewellen, Proc. of ERL 2009, Ithaca, USA, 2009.

[7] A. Arnold, Proc. of SRF 2009, Berlin, Germany, 2009.

[8] J. Knobloch, et al, Proc. of SRF 2003, Lübeck/Travemünde, Germany, 2003.

[9] T. Kamps, Proc. of HBHAP 2009, Los Angeles, USA, 2009.

[10] S. Belomestnykh, V. Vesherevich, et al, Proc. of SRF 2007, Beijing, China, 2007.

[11] K Flöttmann, ASTRA, a space-charge tracking algorithm.

[12] K. J. Kim, NIM A 275, 201 (1989).

[13] C. Travier, NIM A 340, 26 (1994).

[14] J. Sekutowicz, et al, Proc. of PAC 2009, Vancouver, Canada, 2009.

[15] D. Janssen, et al, NIM A 507, 314 (2003).

[16] J. Smedley, T. Rao, J. Sekutowicz, PRST-AB 11, 013502, 2008.

[17] D. H. Dowell, S. Z. Bethel, K. D. Friddell, NIM A 356, 1995.